

A STUDY OF THE TECHNIQUE OF ELECTROCHEMILUMINESCENCE
IN DETERMINING POINTS OF SEPARATION AND TRANSITION

by

LT. FREDERICK GEORGE ADAMS, USN
B.S., United States Naval Academy
(1956)

and

LT. MARTIN GEORGE HILL, USN
B.S., United States Naval Academy
(1958)

SUBMITTED TO THE DEPARTMENT OF NAVAL ARCHITECTURE AND MARINE
ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR
THE MASTER OF SCIENCE DEGREE IN NAVAL ARCHITECTURE AND
MARINE ENGINEERING AND THE PROFESSIONAL DEGREE,
NAVAL ENGINEER

at the

MASSACHUSETTS INSTITUTE of
TECHNOLOGY

May, 1965

DUDLEY KNOX LIBRARY
NAVAL POSTGRADUATE SCHOOL
MONTEREY, CA 93943-5101

U. S. Naval Postgraduate School
Monterey, California

301158A 2511
244
9 2100A

A STUDY OF THE TECHNIQUE OF ELECTROCHEMILUMINESCENCE
IN DETERMINING POINTS OF SEPARATION AND TRANSITION

by

LT. FREDERICK GEORGE ADAMS, USN
B.S., United States Naval Academy
(1956)

and

LT. MARTIN GEORGE HILL, USN
B.S., United States Naval Academy
(1958)

SUBMITTED TO THE DEPARTMENT OF NAVAL ARCHITECTURE AND MARINE
ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR
THE MASTER OF SCIENCE DEGREE IN NAVAL ARCHITECTURE AND
MARINE ENGINEERING AND THE PROFESSIONAL DEGREE,
NAVAL ENGINEER

at the

MASSACHUSETTS INSTITUTE of
TECHNOLOGY

May, 1965

Signature of Authors

.
Department of Naval Architecture and
Marine Engineering, May 21, 1965

Certified by
Thesis Supervisor

Accepted by
Chairman, Departmental Committee
on Graduate Students

A STUDY OF THE TECHNIQUE OF ELECTROCHEMILUMINESCENCE
IN DETERMINING POINTS OF SEPARATION AND TRANSITION

by

Lt. Frederick George Adams, USN

and

Lt. Martin George Hill, USN

Submitted to the Department of Naval Architecture and Marine Engineering on May 21, 1965, in partial fulfillment of the requirements for the Master of Science Degree in Naval Architecture and Marine Engineering and the Professional Degree, Naval Engineer.

ABSTRACT

Experiments were performed to study the technique of electrochemiluminescence for observing separation and transition in liquid flow over a body. The apparatus used was a gravity blowdown tunnel with two cylindrical test sections each 36 inches long and 2 inches and 4 inches in diameter, respectively.

The separation experiments were conducted on flat plates and cylinders. On the cylinders (0.5- and 1.5-inch diameter) a well-defined dark line was observed at approximately 89° from the leading edge in the Reynolds number range from 5.7×10^3 to 1.3×10^5 . The lines were lines of separation as verified by photographs taken of smoke flow over one of the cylinders in a wind tunnel and also by comparing the position of the lines with experimental observations reported by Schlichting. A 5-inch long flat plate model was inclined at various angles of attack from 0.5° to 13.1° and a dark region was observed behind the leading edge in the Reynolds number range from 1.28×10^5 to 4.3×10^5 (based on a 5-inch length). Photographs taken of smoke flow over an inclined flat plate in a wind tunnel indicated that the dark region observed was the region of separation.

The transition studies were conducted by passing the chemiluminescent solution over a 30-inch long flat plate at zero angle of incidence with a maximum Reynolds number of 6.3×10^6 . No phenomenon was observed that could be directly related to transition.

Thesis Supervisor: George S. Springer

Title: Assistant Professor of Mechanical Engineering

SECRET

82

THE UNIVERSITY OF CHICAGO PRESS

15

THE UNIVERSITY OF CHICAGO

and the President of the Navy Department, Mr. Nathan S. Pusey, in a letter dated May 21, 1951, in which he stated that the Navy Department had received a letter from the Department of State, dated May 17, 1951, in which the Department of State had requested that the Navy Department be kept advised of any information received from the Navy Department regarding the activities of the Communist Party, U.S.A., in the United States and its territories.

PLANTATION

and 1/2 inches in diameter, made of steel.

[illegible]

There is no evidence to suggest that the above information was obtained from any source other than the confidential source mentioned above.

DATE: 10/10/1964

Approved: _____ Date: _____

ACKNOWLEDGMENTS

The authors wish to express their appreciation to Professor George S. Springer, Department of Mechanical Engineering, Massachusetts Institute of Technology, for his many suggestions, constructive criticisms, and continuous encouragement and to Professor Hal L. Moses, Department of Mechanical Engineering, Massachusetts Institute of Technology, for making available a wind tunnel at the Gas Turbine Laboratory.

This project was supported in part by the United States Navy and by a Shell Companies Foundation research grant to the Mechanical Engineering Department, Massachusetts Institute of Technology. This financial aid is gratefully acknowledged.

RECOMMENDATIONS

The authors wish to express their appreciation to Professor George H. Spurr, Department of Geological Engineering, Mining, and Metallurgical Engineering, for his very helpful suggestions, criticisms, and editorial assistance throughout the preparation of this manuscript. The authors also wish to express their appreciation to the Department of Geological Engineering, Mining, and Metallurgical Engineering, for the facilities and equipment provided for the completion of this work.

This project was supported in part by the United States Navy and by a Social Sciences Research Council grant to the Geological Engineering, Mining, and Metallurgical Department. The authors also wish to express their appreciation to the following individuals for their assistance in the completion of this work:

TABLE OF CONTENTS

	Page
ABSTRACT	2
ACKNOWLEDGMENTS	3
TABLE OF CONTENTS	4
LIST OF FIGURES	5
I. INTRODUCTION	7
II. PROCEDURE	9
A. Experimental Apparatus	9
B. Electrochemical Solution	20
III. DISCUSSION OF RESULTS	22
A. General	22
B. Circular Cylinder	22
C. Flat Plate	25
D. Transition	34
IV. CONCLUSIONS	39
V. REFERENCES	40
VI. APPENDICES	43
A. Details of Chemiluminescent Solution	44
B. Literature Survey of Flow Separation	45

TABLE OF CONTENTS

1	FOREWORD
2	ACKNOWLEDGMENTS
3	LIST OF FIGURES
4	LIST OF TABLES
5	ABBREVIATIONS
6	SYMBOLS
7	1. INTRODUCTION
8	2. THEORETICAL BACKGROUND
9	3. EXPERIMENTAL PROCEDURE
10	4. RESULTS AND DISCUSSION
11	5. CONCLUSIONS
12	6. REFERENCES
13	7. APPENDICES
14	8. INDEX
15	9. LIST OF FIGURES
16	10. LIST OF TABLES
17	11. ABBREVIATIONS
18	12. SYMBOLS
19	13. 1. INTRODUCTION
20	14. 2. THEORETICAL BACKGROUND
21	15. 3. EXPERIMENTAL PROCEDURE
22	16. 4. RESULTS AND DISCUSSION
23	17. 5. CONCLUSIONS
24	18. 6. REFERENCES
25	19. 7. APPENDICES
26	20. 8. INDEX
27	21. 9. LIST OF FIGURES
28	22. 10. LIST OF TABLES
29	23. 11. ABBREVIATIONS
30	24. 12. SYMBOLS
31	25. 1. INTRODUCTION
32	26. 2. THEORETICAL BACKGROUND
33	27. 3. EXPERIMENTAL PROCEDURE
34	28. 4. RESULTS AND DISCUSSION
35	29. 5. CONCLUSIONS
36	30. 6. REFERENCES
37	31. 7. APPENDICES
38	32. 8. INDEX
39	33. 9. LIST OF FIGURES
40	34. 10. LIST OF TABLES
41	35. 11. ABBREVIATIONS
42	36. 12. SYMBOLS
43	37. 1. INTRODUCTION
44	38. 2. THEORETICAL BACKGROUND
45	39. 3. EXPERIMENTAL PROCEDURE
46	40. 4. RESULTS AND DISCUSSION
47	41. 5. CONCLUSIONS
48	42. 6. REFERENCES
49	43. 7. APPENDICES
50	44. 8. INDEX
51	45. 9. LIST OF FIGURES
52	46. 10. LIST OF TABLES
53	47. 11. ABBREVIATIONS
54	48. 12. SYMBOLS
55	49. 1. INTRODUCTION
56	50. 2. THEORETICAL BACKGROUND
57	51. 3. EXPERIMENTAL PROCEDURE
58	52. 4. RESULTS AND DISCUSSION
59	53. 5. CONCLUSIONS
60	54. 6. REFERENCES
61	55. 7. APPENDICES
62	56. 8. INDEX
63	57. 9. LIST OF FIGURES
64	58. 10. LIST OF TABLES
65	59. 11. ABBREVIATIONS
66	60. 12. SYMBOLS
67	61. 1. INTRODUCTION
68	62. 2. THEORETICAL BACKGROUND
69	63. 3. EXPERIMENTAL PROCEDURE
70	64. 4. RESULTS AND DISCUSSION
71	65. 5. CONCLUSIONS
72	66. 6. REFERENCES
73	67. 7. APPENDICES
74	68. 8. INDEX
75	69. 9. LIST OF FIGURES
76	70. 10. LIST OF TABLES
77	71. 11. ABBREVIATIONS
78	72. 12. SYMBOLS
79	73. 1. INTRODUCTION
80	74. 2. THEORETICAL BACKGROUND
81	75. 3. EXPERIMENTAL PROCEDURE
82	76. 4. RESULTS AND DISCUSSION
83	77. 5. CONCLUSIONS
84	78. 6. REFERENCES
85	79. 7. APPENDICES
86	80. 8. INDEX
87	81. 9. LIST OF FIGURES
88	82. 10. LIST OF TABLES
89	83. 11. ABBREVIATIONS
90	84. 12. SYMBOLS
91	85. 1. INTRODUCTION
92	86. 2. THEORETICAL BACKGROUND
93	87. 3. EXPERIMENTAL PROCEDURE
94	88. 4. RESULTS AND DISCUSSION
95	89. 5. CONCLUSIONS
96	90. 6. REFERENCES
97	91. 7. APPENDICES
98	92. 8. INDEX
99	93. 9. LIST OF FIGURES
100	94. 10. LIST OF TABLES
101	95. 11. ABBREVIATIONS
102	96. 12. SYMBOLS
103	97. 1. INTRODUCTION
104	98. 2. THEORETICAL BACKGROUND
105	99. 3. EXPERIMENTAL PROCEDURE
106	100. 4. RESULTS AND DISCUSSION
107	101. 5. CONCLUSIONS
108	102. 6. REFERENCES
109	103. 7. APPENDICES
110	104. 8. INDEX
111	105. 9. LIST OF FIGURES
112	106. 10. LIST OF TABLES
113	107. 11. ABBREVIATIONS
114	108. 12. SYMBOLS
115	109. 1. INTRODUCTION
116	110. 2. THEORETICAL BACKGROUND
117	111. 3. EXPERIMENTAL PROCEDURE
118	112. 4. RESULTS AND DISCUSSION
119	113. 5. CONCLUSIONS
120	114. 6. REFERENCES
121	115. 7. APPENDICES
122	116. 8. INDEX
123	117. 9. LIST OF FIGURES
124	118. 10. LIST OF TABLES
125	119. 11. ABBREVIATIONS
126	120. 12. SYMBOLS
127	121. 1. INTRODUCTION
128	122. 2. THEORETICAL BACKGROUND
129	123. 3. EXPERIMENTAL PROCEDURE
130	124. 4. RESULTS AND DISCUSSION
131	125. 5. CONCLUSIONS
132	126. 6. REFERENCES
133	127. 7. APPENDICES
134	128. 8. INDEX
135	129. 9. LIST OF FIGURES
136	130. 10. LIST OF TABLES
137	131. 11. ABBREVIATIONS
138	132. 12. SYMBOLS
139	133. 1. INTRODUCTION
140	134. 2. THEORETICAL BACKGROUND
141	135. 3. EXPERIMENTAL PROCEDURE
142	136. 4. RESULTS AND DISCUSSION
143	137. 5. CONCLUSIONS
144	138. 6. REFERENCES
145	139. 7. APPENDICES
146	140. 8. INDEX
147	141. 9. LIST OF FIGURES
148	142. 10. LIST OF TABLES
149	143. 11. ABBREVIATIONS
150	144. 12. SYMBOLS
151	145. 1. INTRODUCTION
152	146. 2. THEORETICAL BACKGROUND
153	147. 3. EXPERIMENTAL PROCEDURE
154	148. 4. RESULTS AND DISCUSSION
155	149. 5. CONCLUSIONS
156	150. 6. REFERENCES
157	151. 7. APPENDICES
158	152. 8. INDEX
159	153. 9. LIST OF FIGURES
160	154. 10. LIST OF TABLES
161	155. 11. ABBREVIATIONS
162	156. 12. SYMBOLS
163	157. 1. INTRODUCTION
164	158. 2. THEORETICAL BACKGROUND
165	159. 3. EXPERIMENTAL PROCEDURE
166	160. 4. RESULTS AND DISCUSSION
167	161. 5. CONCLUSIONS
168	162. 6. REFERENCES
169	163. 7. APPENDICES
170	164. 8. INDEX
171	165. 9. LIST OF FIGURES
172	166. 10. LIST OF TABLES
173	167. 11. ABBREVIATIONS
174	168. 12. SYMBOLS
175	169. 1. INTRODUCTION
176	170. 2. THEORETICAL BACKGROUND
177	171. 3. EXPERIMENTAL PROCEDURE
178	172. 4. RESULTS AND DISCUSSION
179	173. 5. CONCLUSIONS
180	174. 6. REFERENCES
181	175. 7. APPENDICES
182	176. 8. INDEX
183	177. 9. LIST OF FIGURES
184	178. 10. LIST OF TABLES
185	179. 11. ABBREVIATIONS
186	180. 12. SYMBOLS
187	181. 1. INTRODUCTION
188	182. 2. THEORETICAL BACKGROUND
189	183. 3. EXPERIMENTAL PROCEDURE
190	184. 4. RESULTS AND DISCUSSION
191	185. 5. CONCLUSIONS
192	186. 6. REFERENCES
193	187. 7. APPENDICES
194	188. 8. INDEX
195	189. 9. LIST OF FIGURES
196	190. 10. LIST OF TABLES
197	191. 11. ABBREVIATIONS
198	192. 12. SYMBOLS
199	193. 1. INTRODUCTION
200	194. 2. THEORETICAL BACKGROUND
201	195. 3. EXPERIMENTAL PROCEDURE
202	196. 4. RESULTS AND DISCUSSION
203	197. 5. CONCLUSIONS
204	198. 6. REFERENCES
205	199. 7. APPENDICES
206	200. 8. INDEX
207	201. 9. LIST OF FIGURES
208	202. 10. LIST OF TABLES
209	203. 11. ABBREVIATIONS
210	204. 12. SYMBOLS
211	205. 1. INTRODUCTION
212	206. 2. THEORETICAL BACKGROUND
213	207. 3. EXPERIMENTAL PROCEDURE
214	208. 4. RESULTS AND DISCUSSION
215	209. 5. CONCLUSIONS
216	210. 6. REFERENCES
217	211. 7. APPENDICES
218	212. 8. INDEX
219	213. 9. LIST OF FIGURES
220	214. 10. LIST OF TABLES
221	215. 11. ABBREVIATIONS
222	216. 12. SYMBOLS
223	217. 1. INTRODUCTION
224	218. 2. THEORETICAL BACKGROUND
225	219. 3. EXPERIMENTAL PROCEDURE
226	220. 4. RESULTS AND DISCUSSION
227	221. 5. CONCLUSIONS
228	222. 6. REFERENCES
229	223. 7. APPENDICES
230	224. 8. INDEX
231	225. 9. LIST OF FIGURES
232	226. 10. LIST OF TABLES
233	227. 11. ABBREVIATIONS
234	228. 12. SYMBOLS
235	229. 1. INTRODUCTION
236	230. 2. THEORETICAL BACKGROUND
237	231. 3. EXPERIMENTAL PROCEDURE
238	232. 4. RESULTS AND DISCUSSION
239	233. 5. CONCLUSIONS
240	234. 6. REFERENCES
241	235. 7. APPENDICES
242	236. 8. INDEX
243	237. 9. LIST OF FIGURES
244	238. 10. LIST OF TABLES
245	239. 11. ABBREVIATIONS
246	240. 12. SYMBOLS
247	241. 1. INTRODUCTION
248	242. 2. THEORETICAL BACKGROUND
249	243. 3. EXPERIMENTAL PROCEDURE
250	244. 4. RESULTS AND DISCUSSION
251	245. 5. CONCLUSIONS
252	246. 6. REFERENCES
253	247. 7. APPENDICES
254	248. 8. INDEX
255	249. 9. LIST OF FIGURES
256	250. 10. LIST OF TABLES
257	251. 11. ABBREVIATIONS
258	252. 12. SYMBOLS
259	253. 1. INTRODUCTION
260	254. 2. THEORETICAL BACKGROUND
261	255. 3. EXPERIMENTAL PROCEDURE
262	256. 4. RESULTS AND DISCUSSION
263	257. 5. CONCLUSIONS
264	258. 6. REFERENCES
265	259. 7. APPENDICES
266	260. 8. INDEX
267	261. 9. LIST OF FIGURES
268	262. 10. LIST OF TABLES
269	263. 11. ABBREVIATIONS
270	264. 12. SYMBOLS
271	265. 1. INTRODUCTION
272	266. 2. THEORETICAL BACKGROUND
273	267. 3. EXPERIMENTAL PROCEDURE
274	268. 4. RESULTS AND DISCUSSION
275	269. 5. CONCLUSIONS
276	270. 6. REFERENCES
277	271. 7. APPENDICES
278	272. 8. INDEX
279	273. 9. LIST OF FIGURES
280	274. 10. LIST OF TABLES
281	275. 11. ABBREVIATIONS
282	276. 12. SYMBOLS
283	277. 1. INTRODUCTION
284	278. 2. THEORETICAL BACKGROUND
285	279. 3. EXPERIMENTAL PROCEDURE
286	280. 4. RESULTS AND DISCUSSION
287	281. 5. CONCLUSIONS
288	282. 6. REFERENCES
289	283. 7. APPENDICES
290	284. 8. INDEX
291	285. 9. LIST OF FIGURES
292	286. 10. LIST OF TABLES
293	287. 11. ABBREVIATIONS
294	288. 12. SYMBOLS
295	289. 1. INTRODUCTION
296	290. 2. THEORETICAL BACKGROUND
297	291. 3. EXPERIMENTAL PROCEDURE
298	292. 4. RESULTS AND DISCUSSION
299	293. 5. CONCLUSIONS
300	294. 6. REFERENCES
301	295. 7. APPENDICES
302	296. 8. INDEX
303	297. 9. LIST OF FIGURES
304	298. 10. LIST OF TABLES
305	299. 11. ABBREVIATIONS
306	300. 12. SYMBOLS
307	301. 1. INTRODUCTION
308	302. 2. THEORETICAL BACKGROUND
309	303. 3. EXPERIMENTAL PROCEDURE
310	304. 4. RESULTS AND DISCUSSION
311	305. 5. CONCLUSIONS
312	306. 6. REFERENCES
313	307. 7. APPENDICES
314	308. 8. INDEX
315	309. 9. LIST OF FIGURES
316	310. 10. LIST OF TABLES
317	311. 11. ABBREVIATIONS
318	312. 12. SYMBOLS
319	313. 1. INTRODUCTION
320	314. 2. THEORETICAL BACKGROUND
321	315. 3. EXPERIMENTAL PROCEDURE
322	316. 4. RESULTS AND DISCUSSION
323	317. 5. CONCLUSIONS
324	318. 6. REFERENCES
325	319. 7. APPENDICES
326	320. 8. INDEX
327	321. 9. LIST OF FIGURES
328	322. 10. LIST OF TABLES
329	323. 11. ABBREVIATIONS
330	324. 12. SYMBOLS
331	325. 1. INTRODUCTION
332	326. 2. THEORETICAL BACKGROUND
333	327. 3. EXPERIMENTAL PROCEDURE
334	328. 4. RESULTS AND DISCUSSION
335	329. 5. CONCLUSIONS
336	330. 6. REFERENCES
337	331. 7. APPENDICES
338	332. 8. INDEX
339	333. 9. LIST OF FIGURES
340	334. 10. LIST OF TABLES
341	335. 11. ABBREVIATIONS
342	336. 12. SYMBOLS
343	337. 1. INTRODUCTION
344	338. 2. THEORETICAL BACKGROUND
345	339. 3. EXPERIMENTAL PROCEDURE
346	340. 4. RESULTS AND DISCUSSION
347	341. 5. CONCLUSIONS
348	342. 6. REFERENCES
349	343. 7. APPENDICES
350	344. 8. INDEX
351	345. 9. LIST OF FIGURES
352	346. 10. LIST OF TABLES
353	347. 11. ABBREVIATIONS
354	348. 12. SYMBOLS
355	349. 1. INTRODUCTION
356	350. 2. THEORETICAL BACKGROUND
357	351. 3. EXPERIMENTAL PROCEDURE
358	352. 4. RESULTS AND DISCUSSION
359	353. 5. CONCLUSIONS
360	354. 6. REFERENCES
361	355. 7. APPENDICES
362	356. 8. INDEX
363	357. 9. LIST OF FIGURES
364	358. 10. LIST OF TABLES
365	359. 11. ABBREVIATIONS
366	360. 12. SYMBOLS
367	361. 1. INTRODUCTION
368	362. 2. THEORETICAL BACKGROUND
369	363. 3. EXPERIMENTAL PROCEDURE
370	364. 4. RESULTS AND DISCUSSION
371	365. 5. CONCLUSIONS
372	366. 6. REFERENCES
373	367. 7. APPENDICES
374	368. 8. INDEX
375	369. 9. LIST OF FIGURES
376	370. 10. LIST OF TABLES
377	371. 11. ABBREVIATIONS
378	372. 12. SYMBOLS
379	373. 1. INTRODUCTION
380	374. 2. THEORETICAL BACKGROUND
381	375. 3. EXPERIMENTAL PROCEDURE
382	376. 4. RESULTS AND DISCUSSION
383	377. 5. CONCLUSIONS
384	378. 6. REFERENCES
385	379. 7. APPENDICES
386	380. 8. INDEX</

LIST OF FIGURES

		Page
FIGURE	1. TEST APPARATUS	11
FIGURE	2. TEST SECTION	12
FIGURE	3. VELOCITY PROFILES IN TEST SECTION (FOR TIME AFTER OPENING CONTROL VALVE 12 AND 24 SECONDS; SETTLING TANK FULL)	13
FIGURE	4. VELOCITY PROFILES IN TEST SECTION (FOR TIME AFTER OPENING CONTROL VALVE 36 AND 48 SECONDS; SETTLING TANK FULL)	14
FIGURE	5. VELOCITY PROFILES IN TEST SECTION (FOR TIME AFTER OPENING CONTROL VALVE 6 AND 12 SECONDS; SETTLING TANK HALF FULL)	15
FIGURE	6. VELOCITY PROFILES IN TEST SECTION (FOR TIME AFTER OPENING CONTROL VALVE 18 AND 24 SECONDS; SETTLING TANK HALF FULL)	16
FIGURE	7. VELOCITY - TIME CHARACTERISTICS IN TEST SECTION (SETTLING TANK FULL)	17
FIGURE	8. VELOCITY - TIME CHARACTERISTICS IN TEST SECTION (SETTLING TANK HALF FULL)	18
FIGURE	9. LINE OF SEPARATION ON CYLINDERS	27
	a. Diameter, $d = 1.5$ inches Re (Based on Diameter) = 17,100	
	b. Diameter, $d = 0.5$ inches Re (Based on Diameter) = 5,700	
FIGURE	10. LINE OF SEPARATION ON CYLINDERS AT VARIOUS REYNOLDS NUMBERS (BASED ON CYLINDER DIAMETER OF 0.5 INCHES)	28
	a. Re = 5,700	
	b. Re = 15,100	
	c. Re = 35,300	
	d. Re = 43,300	

2007-08-28

FIGURE	DESCRIPTION
1	FIGURE 1 - THE CHARACTERISTICS IN TEST SECTION (BRITISH RAIL FULL)
2	FIGURE 2 - THE CHARACTERISTICS IN TEST SECTION (BRITISH RAIL FULL)
3	FIGURE 3 - THE CHARACTERISTICS IN TEST SECTION (BRITISH RAIL FULL)
4	FIGURE 4 - THE CHARACTERISTICS IN TEST SECTION (BRITISH RAIL FULL)
5	FIGURE 5 - THE CHARACTERISTICS IN TEST SECTION (BRITISH RAIL FULL)
6	FIGURE 6 - THE CHARACTERISTICS IN TEST SECTION (BRITISH RAIL FULL)
7	FIGURE 7 - THE CHARACTERISTICS IN TEST SECTION (BRITISH RAIL FULL)
8	FIGURE 8 - THE CHARACTERISTICS IN TEST SECTION (BRITISH RAIL FULL)
9	FIGURE 9 - THE CHARACTERISTICS IN TEST SECTION (BRITISH RAIL FULL)
10	FIGURE 10 - THE CHARACTERISTICS IN TEST SECTION (BRITISH RAIL FULL)

	Page
FIGURE 11. LINE OF SEPARATION ON CYLINDERS AT VARIOUS REYNOLDS NUMBERS (BASED ON CYLINDER DIAMETER OF 1.5 INCHES)	29
a. $Re = 17,100$	
b. $Re = 45,300$	
c. $Re = 106,000$	
d. $Re = 130,000$	
FIGURE 12. SEPARATION ON A FLAT PLATE AT VARIOUS REYNOLDS NUMBERS. ANGLE OF ATTACK = 0.5° . REYNOLDS NUMBER (BASED ON PLATE LENGTH OF 5 INCHES)	30
a. $Re = 128,000$	
b. $Re = 253,000$	
c. $Re = 350,000$	
d. $Re = 430,000$	
FIGURE 13. SEPARATION ON A FLAT PLATE AT VARIOUS REYNOLDS NUMBERS. ANGLE OF ATTACK = 2.5° . REYNOLDS NUMBER (BASED ON PLATE LENGTH OF 5 INCHES)	31
a. $Re = 128,000$	
b. $Re = 253,000$	
c. $Re = 350,000$	
d. $Re = 430,000$	
FIGURE 14. SEPARATION ON FLAT PLATE AT VARIOUS ANGLES OF ATTACK. (REYNOLDS NUMBER BASED ON PLATE LENGTH OF 5 INCHES.) $Re = 128,000$	32
a. Angle of Attack = 0.5°	
b. Angle of Attack = 2.5°	
c. Angle of Attack = 3.2°	
d. Angle of Attack = 13.1°	
FIGURE 15. SEPARATION ON FLAT PLATE AND CYLINDER IN WIND TUNNEL. (REYNOLDS NUMBER BASED ON FLAT PLATE LENGTH OF 5 INCHES AND CYLINDER DIAMETER OF 1.5 INCHES)	33
a. Angle of Attack = 10° , $Re = 2,400$	
b. Angle of Attack = 15° , $Re = 2,400$	
c. $Re = 735$	

1947

FIGURE 11.	TIME OF SEPARATION OF CYLINDERS AT VARIOUS ANGLES OF ATTACK. (WIND SPEED 100 MPH, CYLINDER DIAMETER 1.5 INCHES)	30
a.	$\alpha = 11.100$	
b.	$\alpha = 12.700$	
c.	$\alpha = 14.000$	
d.	$\alpha = 15.000$	
FIGURE 12.	SEPARATION OF PLATE FROM A PLATE PLANE AT VARIOUS ANGLES OF ATTACK. (WIND SPEED 100 MPH, PLATE AREA 0.25 SQ. INCHES, PLATE THICKNESS 0.2 INCHES)	30
a.	$\alpha = 12.700$	
b.	$\alpha = 13.300$	
c.	$\alpha = 14.000$	
d.	$\alpha = 15.000$	
FIGURE 13.	SEPARATION OF PLATE FROM A PLATE PLANE AT VARIOUS ANGLES OF ATTACK. (WIND SPEED 100 MPH, PLATE AREA 0.25 SQ. INCHES, PLATE THICKNESS 0.2 INCHES)	31
a.	$\alpha = 12.700$	
b.	$\alpha = 13.300$	
c.	$\alpha = 14.000$	
d.	$\alpha = 15.000$	
FIGURE 14.	SEPARATION OF PLATE FROM A PLATE PLANE AT VARIOUS ANGLES OF ATTACK. (WIND SPEED 100 MPH, PLATE AREA 0.25 SQ. INCHES, PLATE THICKNESS 0.2 INCHES)	32
a.	Angle of Attack = 0.2°	
b.	Angle of Attack = 2.5°	
c.	Angle of Attack = 5.0°	
d.	Angle of Attack = 11.1°	
FIGURE 15.	SEPARATION OF PLATE FROM A PLATE PLANE AND CYLINDER IN WIND TUNNEL. (WIND SPEED 100 MPH, PLATE AREA 0.25 SQ. INCHES, CYLINDER DIAMETER 1.5 INCHES)	33
a.	Angle of Attack = 10° , $\alpha = 2.400$	
b.	Angle of Attack = 12° , $\alpha = 2.400$	
c.	$\alpha = 1.75$	

I. INTRODUCTION

It has long been recognized that fluid flow visualization has played an important part in the development of the science of Fluid Mechanics.^{1*} Electrochemiluminescence offers the possibility of a new flow visualization technique. It is novel in that events in the boundary layer are observed directly, and no extraneous object is introduced into the flow. Chemicals are added to the water, but these are dissolved, and the resulting fluid is a homogeneous solution.

Howland, et al.,² were the first to apply the technique of electrochemiluminescence to fluid flow visualization studies. In this technique a model coated with platinum is immersed in an alkaline solution of Luminol and Hydrogen Peroxide.^{**} The platinum on the model serves as one electrode (the anode), and the other electrode (the cathode) consists of a sheet of aluminum. A continuous blue glow is observed on the surface of the platinum when the potential between the electrodes is approximately one volt D. C. and relative motion exists between the fluid and model. Then patterns are observed in the blue glow which apparently represent flow phenomena (e.g., separation). When the potential is increased to approximately five or six volts between electrodes, the glow patterns tend to detach from the surface of the platinum and trail in the wake of the model. This study treats only phenomena which are observed at the surface of the model.

* Superscripts indicate references at the end of the thesis.

** A detailed description of the solution is given in Appendix A.

Howland, et al.,² working with a small apparatus (essentially a large rotating bowl containing the chemiluminescent solution) observed what they considered were regions of separation and transition on cylinders and flat plates. Schiller³ designed and built an apparatus with a capacity for achieving higher Reynolds numbers than were possible using Howland's apparatus. Schiller, experimenting with flat plates, believed that he was observing separation at various angles of attack on the plates. Springer⁴ showed that in laminar flow the light intensity is governed by mass transfer of the chemiluminescent substance to the surface of the platinum.

The above observations suggest that there is a correlation between the light intensity, observed glow patterns, and events occurring in the boundary layer. This study was undertaken as an attempt to correlate observed glow patterns with events occurring in the boundary layer with particular emphasis on separation and transition. Attempts will be made to observe what are considered to be separation and transition points in the blue glow on various models. The observed points will be compared to existing experimental data and theoretical results where possible to determine whether or not the technique of electrochemiluminescence can be used as a valid flow visualization technique for transition and separation.

II. PROCEDURE

A. Experimental Apparatus

The apparatus used in this study is that designed and built by Schiller.³ It is a gravity blowdown system and is shown in Figure 1. The test section (shown in Figure 2) is a plexiglass tube approximately 36 inches long. The inside diameter of the tube is 4 inches. The model to be studied (e.g., flat plate or cylinder) is placed in the test section, and the test section is then secured in its proper position in the apparatus as shown in Figure 1. The settling tank is filled to the desired level (depending on the length of test run desired) with chemiluminescent solution (the details of which are given in Appendix A), and the anode to cathode potential is established by turning on the D. C. power supply. The power supply used in this study was a Harrison Laboratories, Inc., model 880A Regulated Power Supply with a range of from 0-100 volts and 0-1 amperes. When the control valve is opened, the chemiluminescent solution flows over the model being studied, and photographs are taken of the resulting glow patterns.

The apparatus was designed to approximate slug flow in the test section. During the initial phase of this study, it was necessary to determine whether or not slug flow does in fact exist in the test section. To do this the test section was instrumented with two pitot tubes as shown in Figure 2. The pitot tubes are made of 1/16-inch inside diameter stainless steel tubing. The outside diameter is 3/32 of an inch. The lengths of the tubes are 3-3/4 inches, and their position across the test section is adjustable so that complete coverage

II. EXPERIMENTAL

A. Experimental Apparatus

The apparatus used in this study is shown schematically in Figure 1. It is a fairly standard system and is shown in Figure 1. The test section (shown in Figure 2) is a glass tube with approximately 10 inches long. The inside diameter of the tube is 1 inch. The model to be tested (e.g., flat plate or cylinder) is placed in the test section, and the test section is then covered in the proper way. Also in the apparatus as shown in Figure 1. The section was in filled to the desired level (depending on the degree of heat transfer) with condensed steam (the details of which are given in Appendix A), and the section is equipped with a thermocouple for measuring the D. C. power supply. The power supply used in this study was a Westinghouse Laboratories, Inc., model 6000 regulated power supply with a range of from 0-100 volts and 0-1 ampere. When the section was in operation, the condenser was rotated about 180° over the model being tested, and the condenser was then of the rotating glass section. The apparatus was designed to operate at a pressure of 100 psia. During the initial phase of the study, it was necessary to determine whether or not the flow was in the test section in the test section. To do this the test section was surrounded with two glass tubes as shown in Figure 2. The glass tubes were made of 1/2-inch inside diameter stainless steel tubing. The outside diameter is 3/4 of an inch. The distance of the tubes was 2-1/2 inches, and their position around the test section is adjustable so that complete coverage

of over half of the test section profile is obtained. The tubes are bent to an angle of 90 degrees one inch from one end. The radius of the bend is $3/16$ of an inch. The pitot tubes measure the dynamic pressure only. The static pressure is measured through a static pressure tap which is a $3/32$ -inch hole in the side of the test section adjacent to the pitot tube. The settling tank was filled to the top with approximately 1500 liters of water, and the velocity profile across the test section was measured as the water was released. The measured velocity profiles verified that nearly slug flow exists everywhere in the test section. Figures 3 and 4 show the velocity profiles obtained with the settling tank full (1500 liters) at the start of the run. The maximum velocity of the water in the test section was approximately 10.8 feet per second. Figures 5 and 6 show the velocity profiles obtained when the procedure given above is repeated with the settling tank half full (approximately 750 liters) of water at the start of the run. For this case the maximum velocity of the water in the test section was approximately 10.4 feet per second.

It was determined that the flow is somewhat time dependent, but in any given test run after time $t = 10$ seconds (where t is time after opening the control valve), the velocity vs. time characteristics are flat. They approximate steady state conditions since the velocity decreases .01 feet per second per second after time $t = 10$ seconds. Figures 7 and 8 show the velocity vs. time characteristics for runs with the settling tank full and half full, respectively, at the start of the run. The total run time with a full settling tank is 54 seconds, and the total

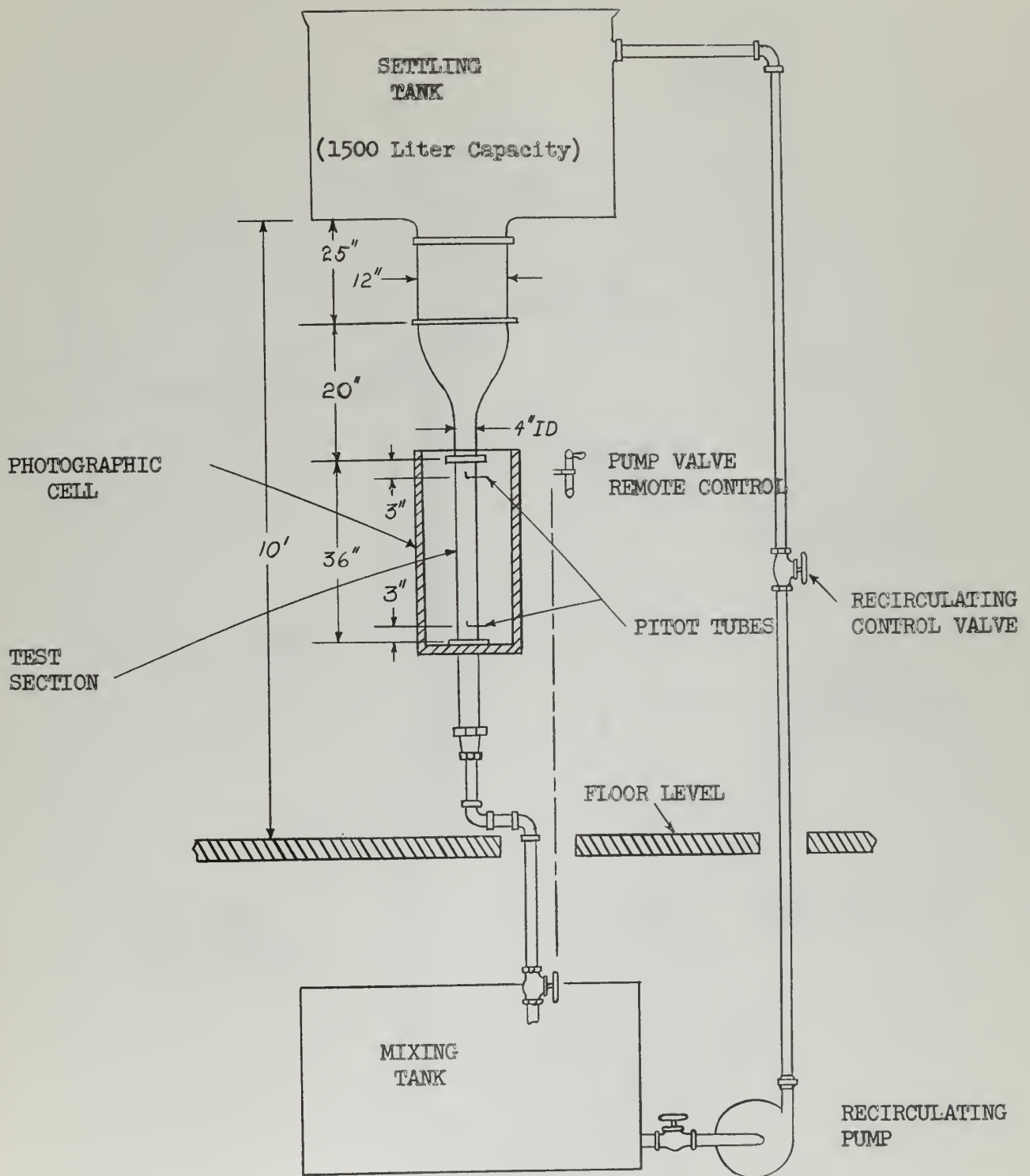


FIGURE 1 TEST APPARATUS

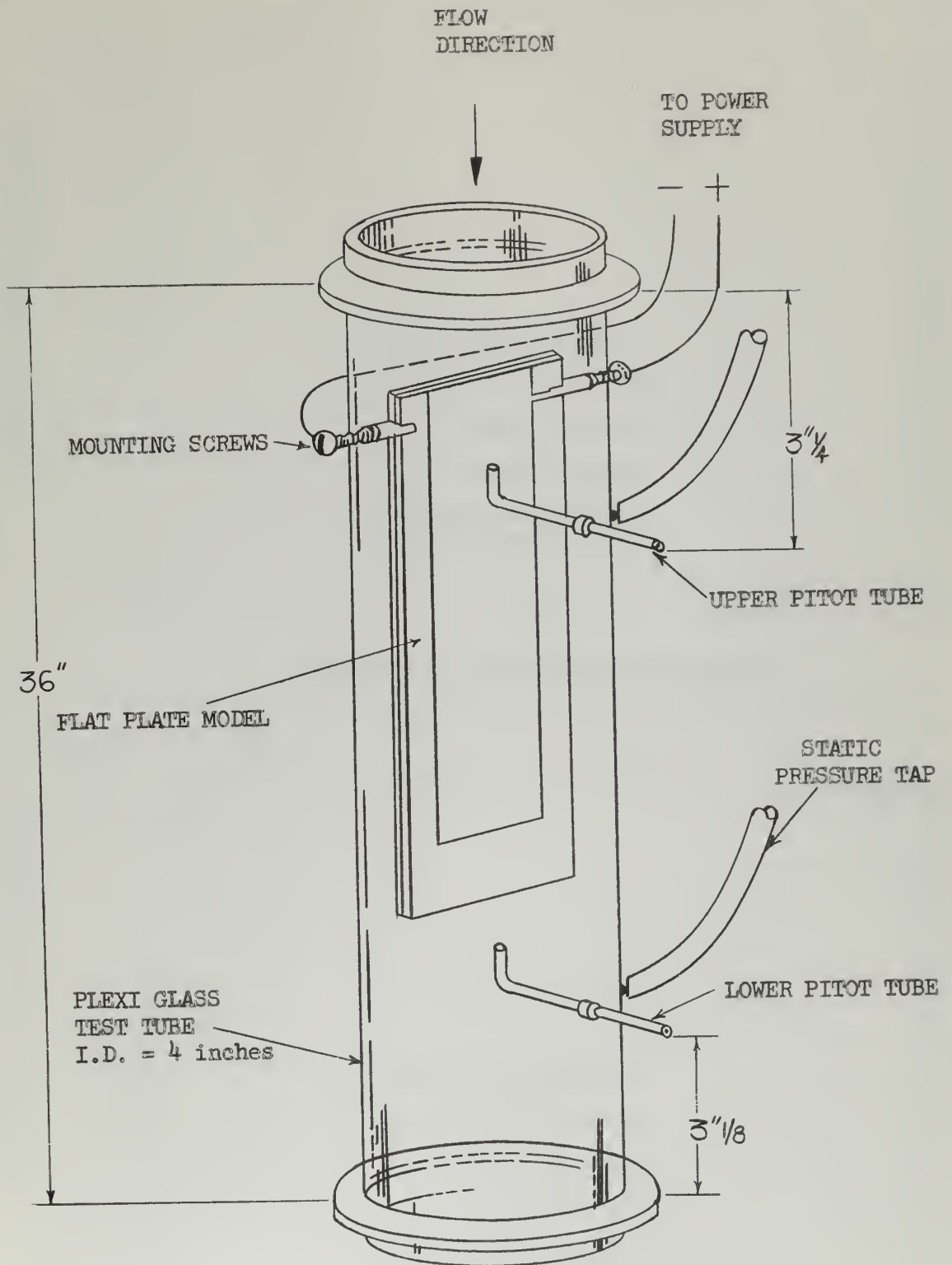


FIGURE 2 TEST SECTION

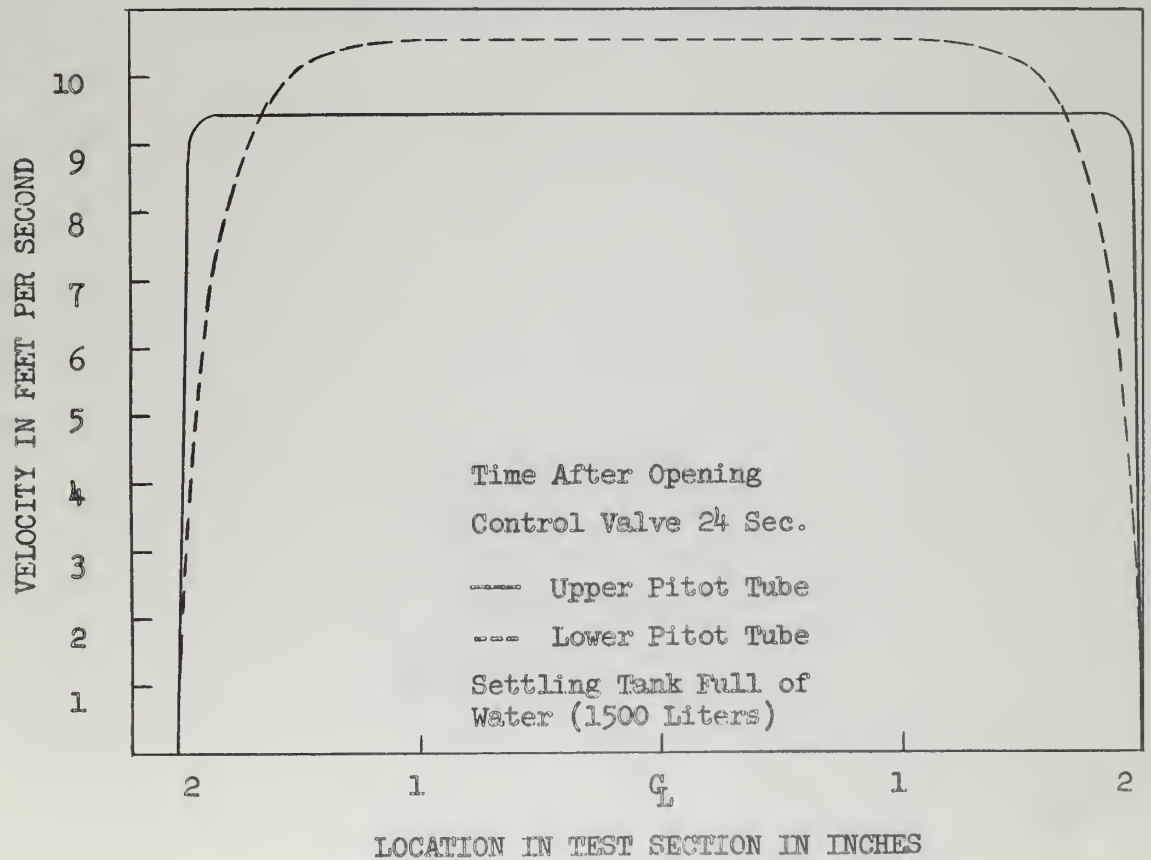
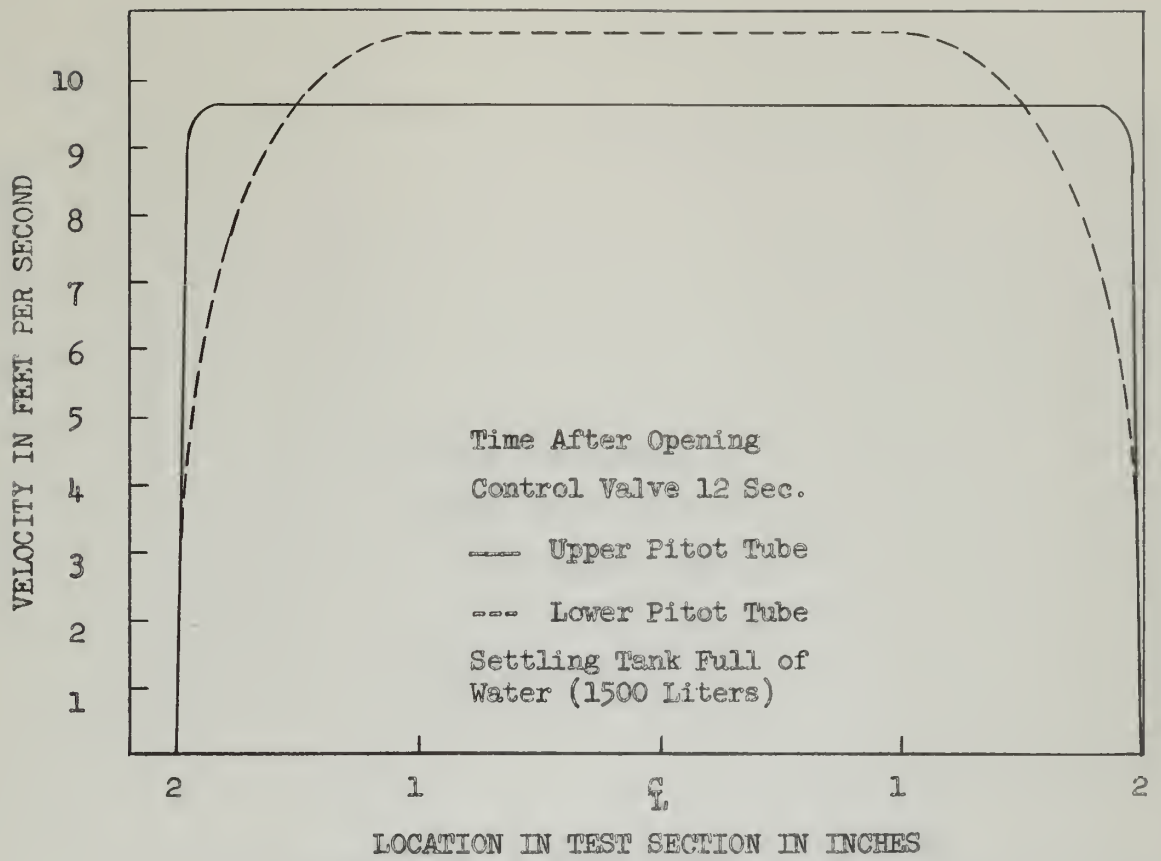


FIGURE 3 VELOCITY PROFILES IN TEST SECTION

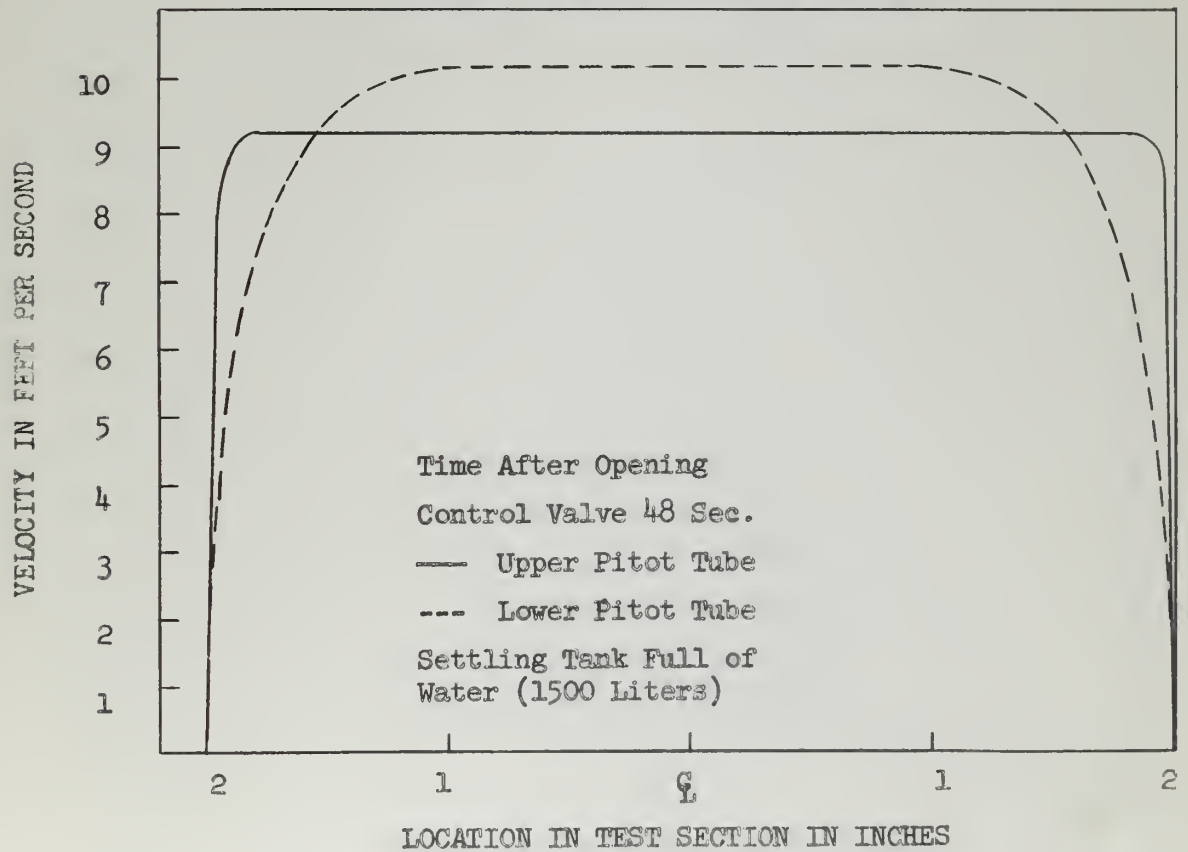
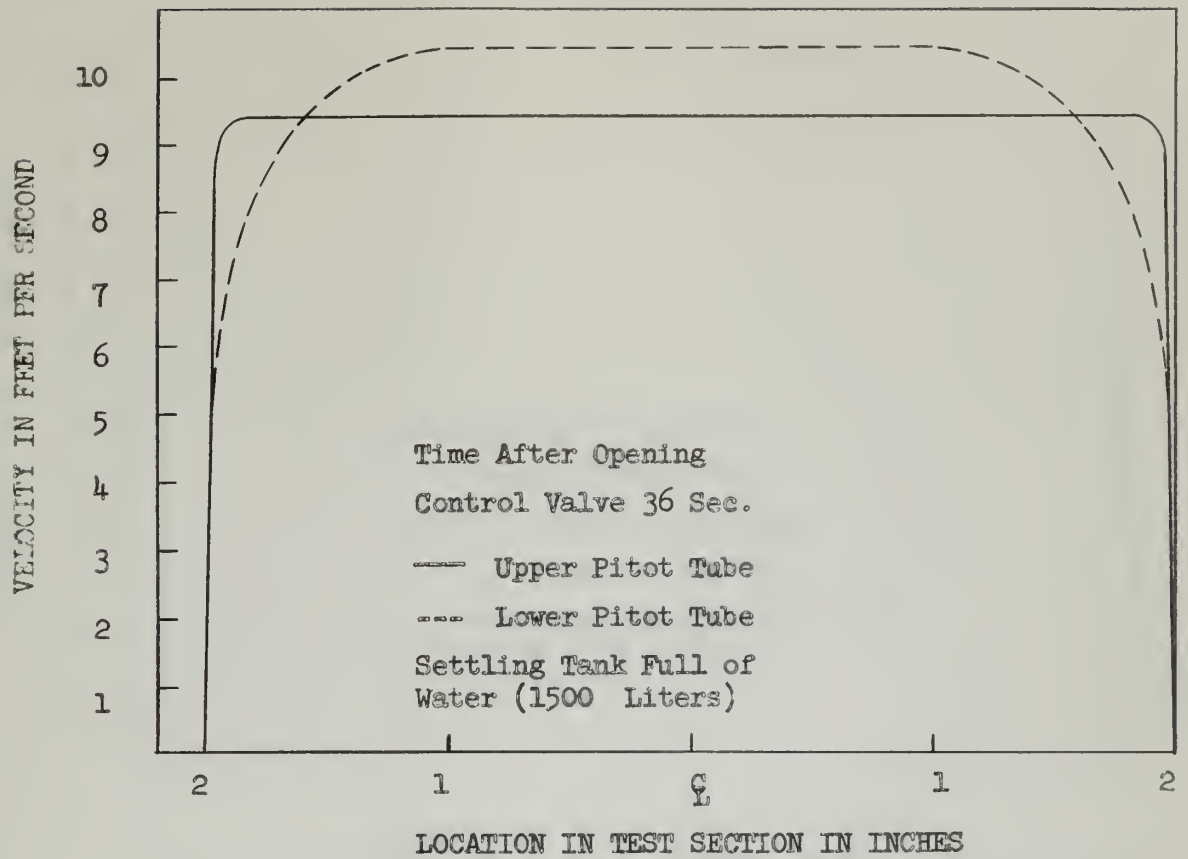


FIGURE 4 VELOCITY PROFILES IN TEST SECTION

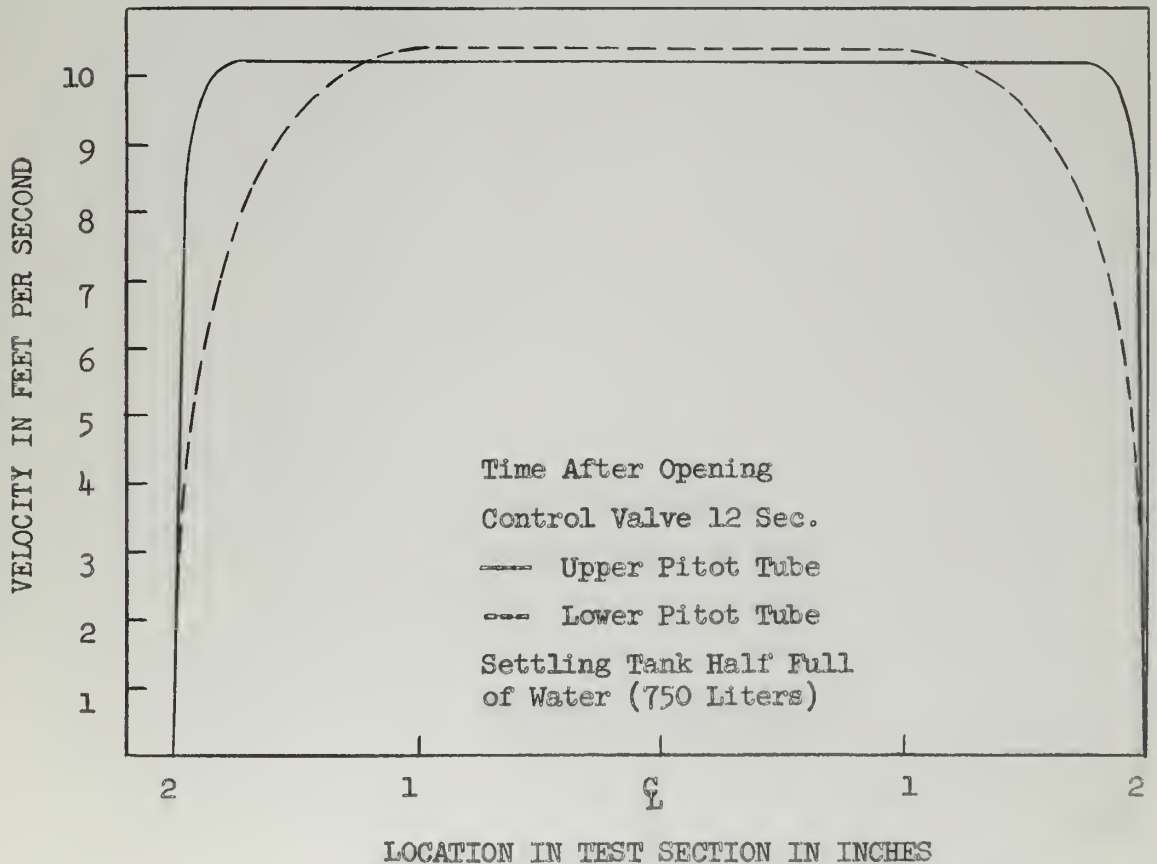
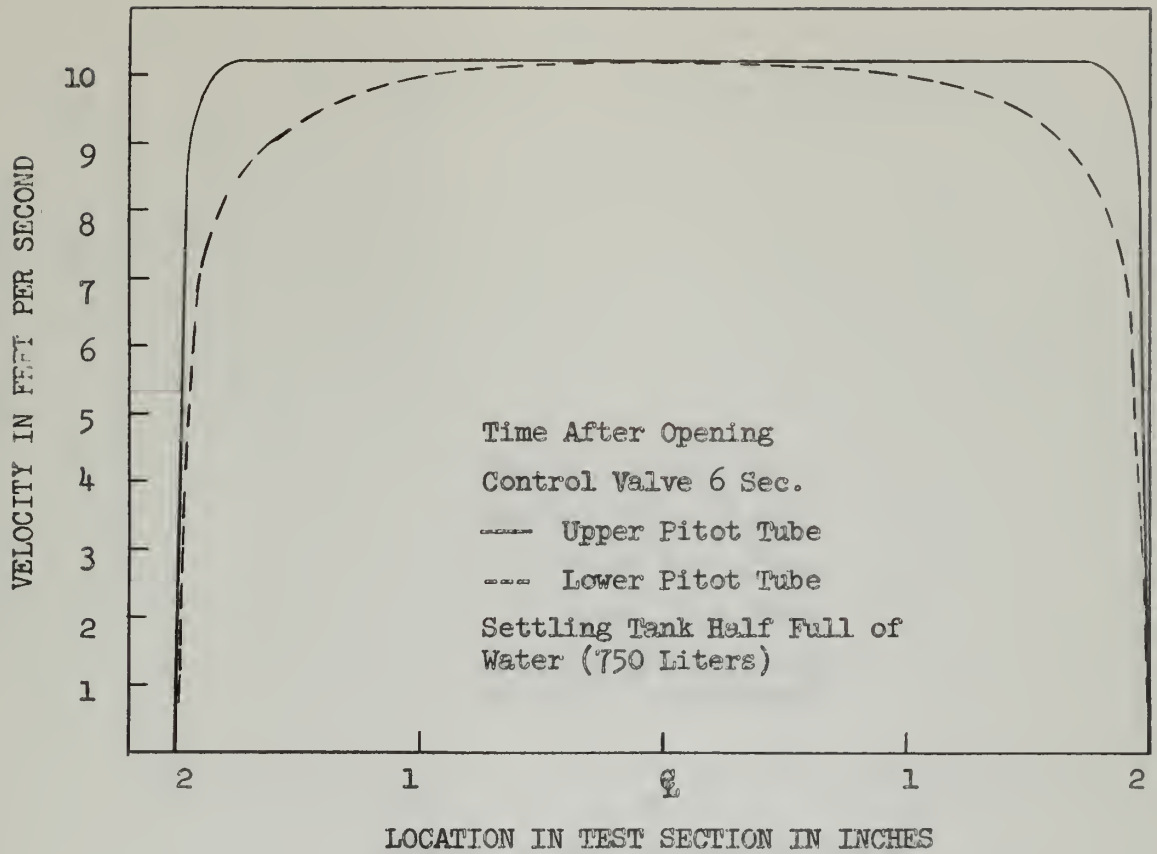


FIGURE 5 VELOCITY PROFILES IN TEST SECTION

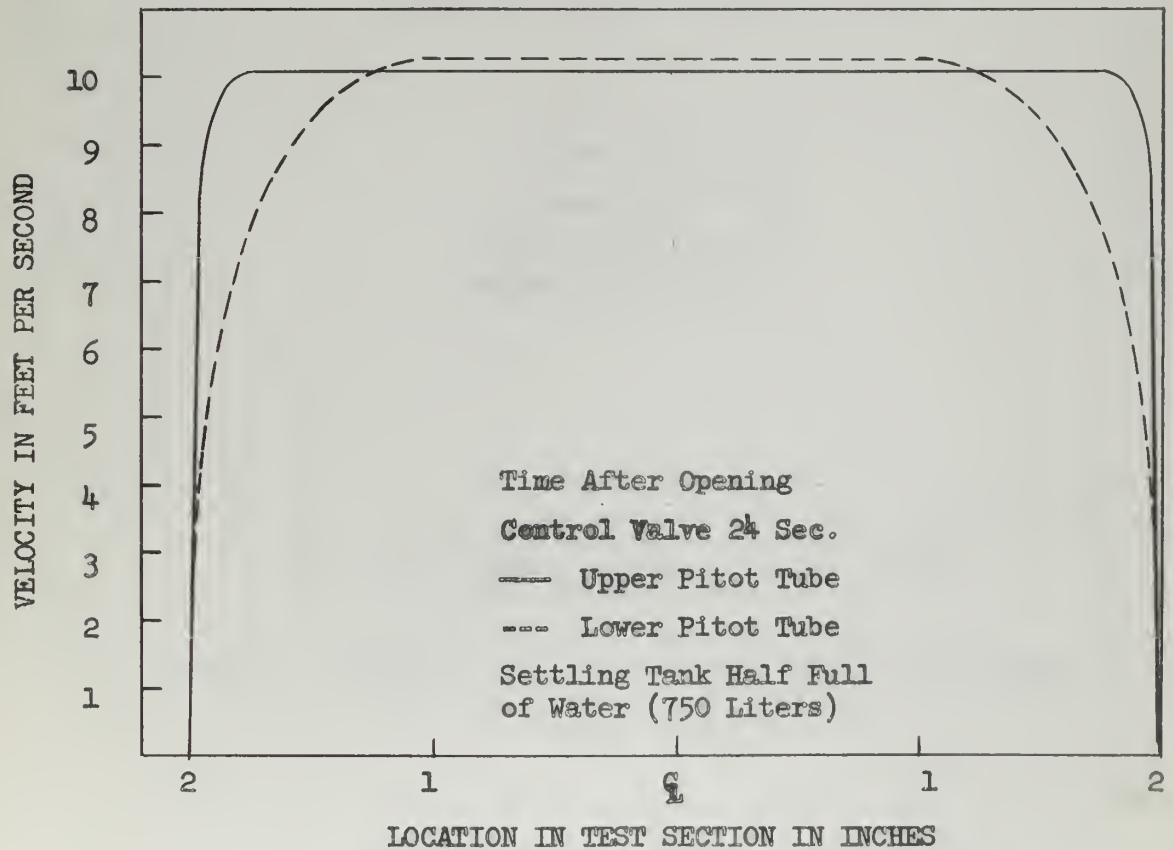
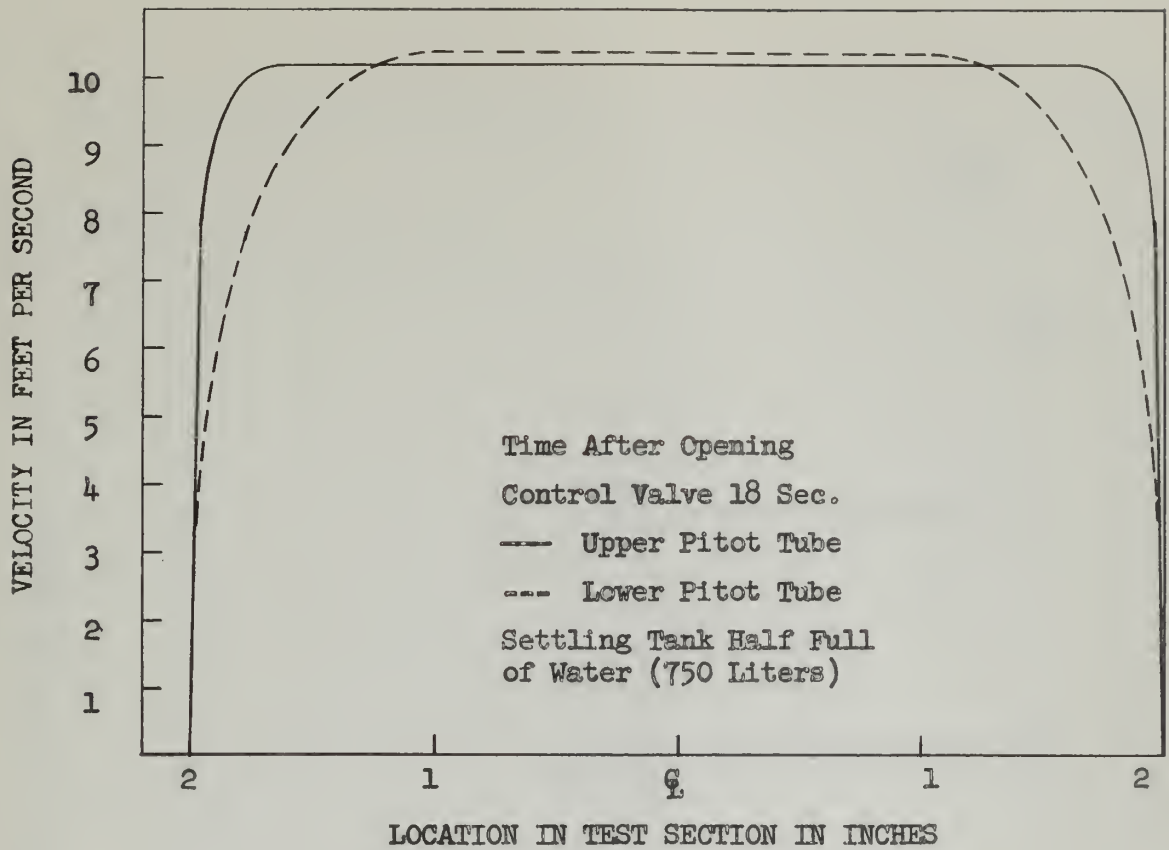


FIGURE 6 VELOCITY PROFILES IN TEST SECTION

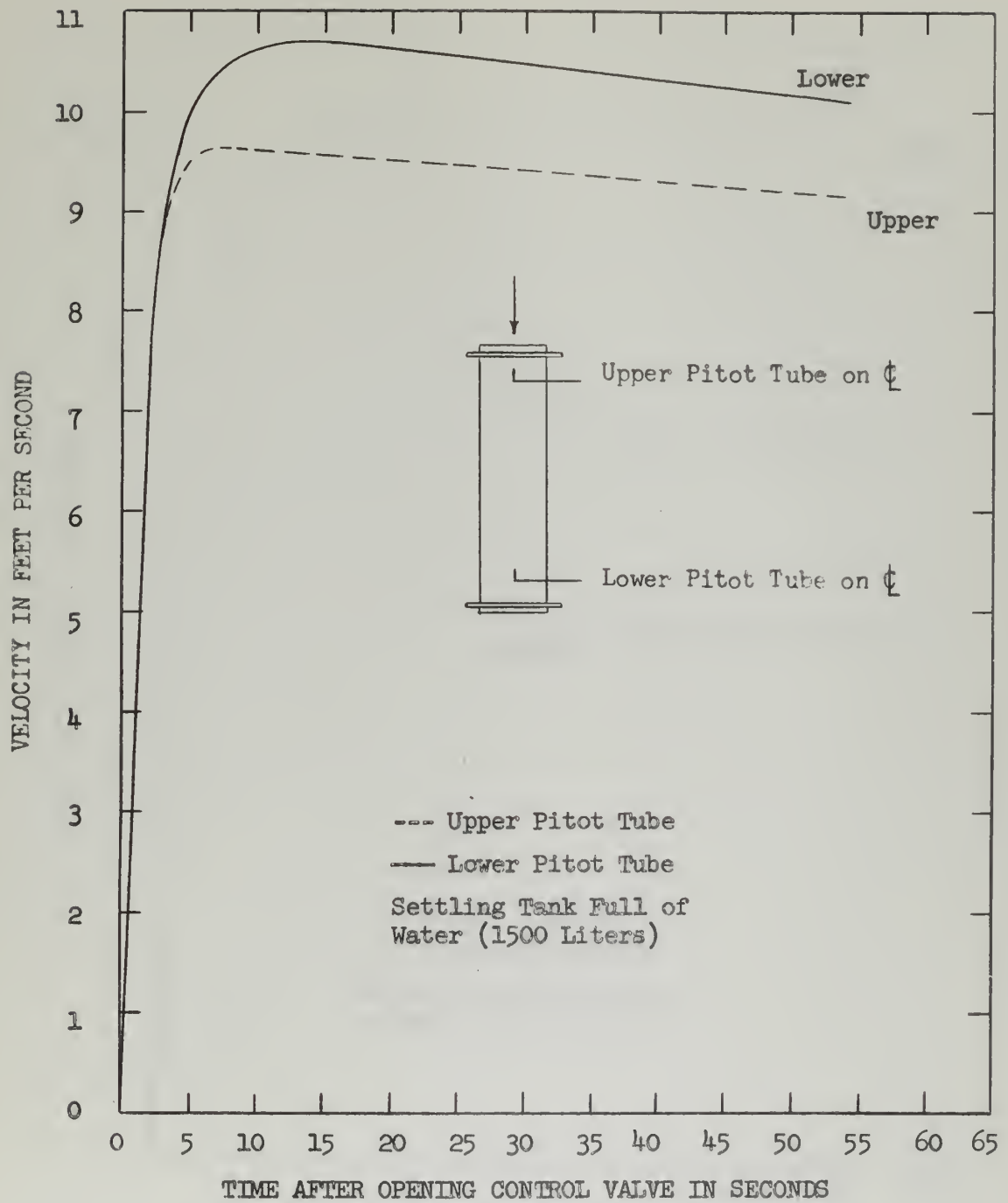


FIGURE 7 VELOCITY - TIME CHARACTERISTICS IN TEST SECTION

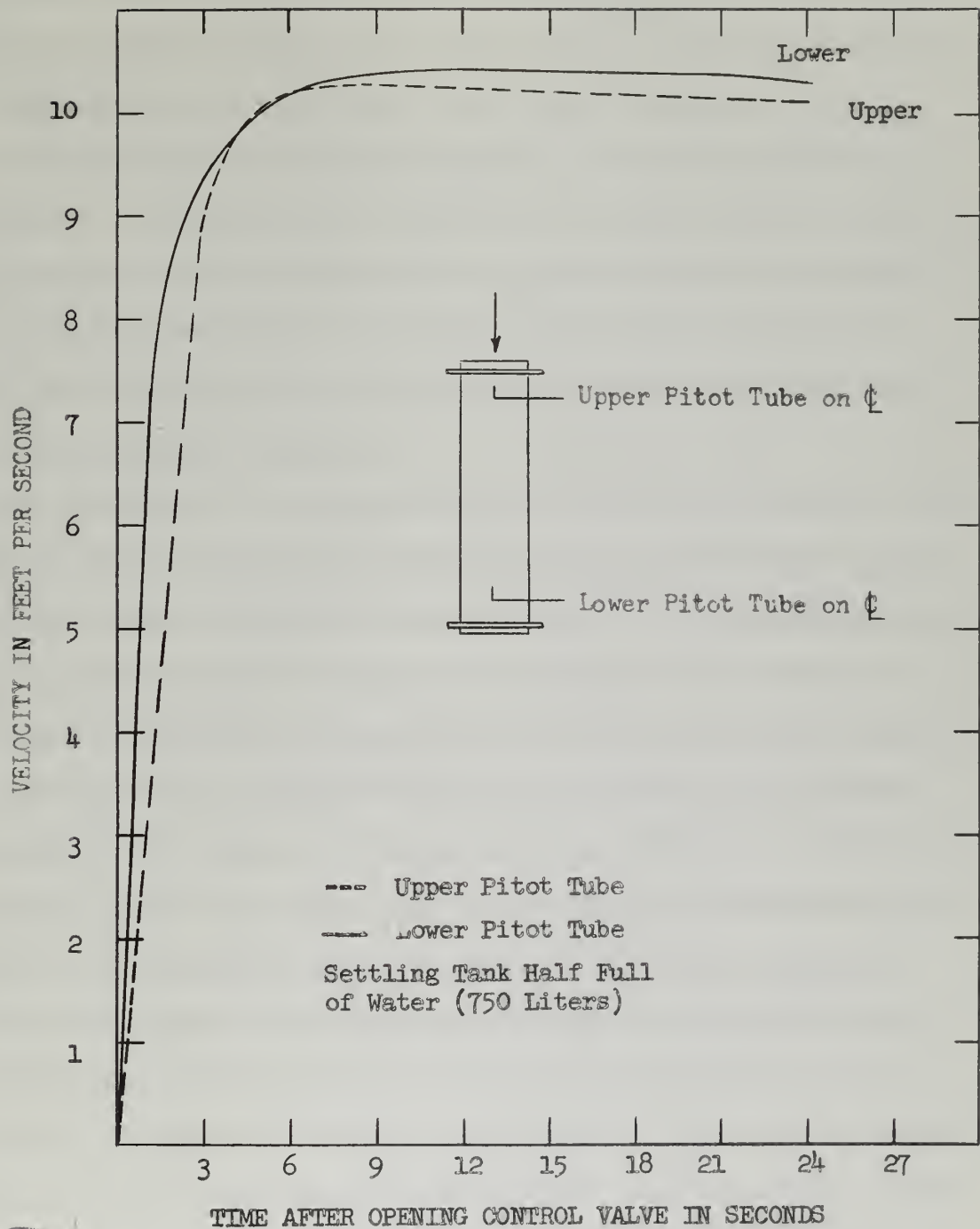


FIGURE 8 VELOCITY - TIME CHARACTERISTICS IN TEST SECTION

time with a half tank is 24 seconds. In the interests of economy and time, all actual test runs with chemiluminescent fluid were made with the settling tank one-half full at the start of the run.

The electrical system used is the same as that described by Schiller.³ It consists of the model either platinum plated or coated with platinum foil as the anode and an aluminum plate as the cathode. The flat plate models used are plexiglass flat plates with platinum foil glued to one surface of the plate and an aluminum plate glued to the other surface. The glue used is a two-part epoxy glue. One cylindrical model used is a 1.5-inch diameter stainless steel cylinder. The cylinder face is electroplated with approximately 0.002 inch of platinum. The ends of the cylinder are not plated. The other cylinder model is a 0.5-inch diameter plexiglas rod with platinum foil glued to its surface. The electrical connections are made through the two screws in the test section (Figure 2) when flat plate models are in the test section. In the case of cylinders the anode connection is made through one screw in the test section, and the cathode connection is made with a small wire attached to the aluminum plate and running out the back of the test section. The cylinder cathode is an aluminum plate which is suspended in the test section and not attached in any way to the cylinder. The anode and cathode are connected to the + and - terminals, respectively, of a D.C. variable power supply. The power supply serves as a switch as well as the means for varying the voltage. During the actual test runs the voltage was adjusted to maintain the maximum light intensity without generating detached glow patterns. It was determined that approximately 3 to 4 volts anode to cathode potential were required.

film with a half inch to 1/4 inch. In the instance of second and third, all optical parts were with glass. The optical parts were with glass. The optical parts were with glass.

The electrical system used in the case is described by

Table 1. It consists of the main electrical system placed in contact with the main film in the main film in the main film.

The main electrical system used in the case is described by

Table 1. It consists of the main electrical system placed in contact with the main film in the main film in the main film. The main electrical system used in the case is described by Table 1. It consists of the main electrical system placed in contact with the main film in the main film in the main film.

The main electrical system used in the case is described by

Table 1. It consists of the main electrical system placed in contact with the main film in the main film in the main film.

The main electrical system used in the case is described by

Table 1. It consists of the main electrical system placed in contact with the main film in the main film in the main film.

The main electrical system used in the case is described by

Table 1. It consists of the main electrical system placed in contact with the main film in the main film in the main film.

The main electrical system used in the case is described by

Table 1. It consists of the main electrical system placed in contact with the main film in the main film in the main film.

The main electrical system used in the case is described by

Table 1. It consists of the main electrical system placed in contact with the main film in the main film in the main film.

The main electrical system used in the case is described by

Table 1. It consists of the main electrical system placed in contact with the main film in the main film in the main film.

The main electrical system used in the case is described by

Table 1. It consists of the main electrical system placed in contact with the main film in the main film in the main film.

The main electrical system used in the case is described by

Late in the study it was determined that the glow on the anode could be obtained if the platinum were replaced with stainless steel. The glow obtained is as intense as that using platinum as the anode. In this case, however, the KOH content of the solution was 0.1 Normal instead of 0.01 Normal as recommended by Howland.² It is not certain what effect the added KOH had on the solution or the electrochemiluminescent process other than to make the solution more alkaline. No attempt was made to investigate the solution or anode material further.

B. Electrochemical Solution

The composition of the solution used is that specified by Schiller.³ This solution differs from Howland's² in that only one third of the amount of potassium chloride is used. Schiller determined that this reduction of KCl makes no apparent change in the glow intensity. The solution is composed of luminol, hydrogen peroxide, potassium chloride, potassium hydroxide, and purified water. The details of the amounts and functions of each chemical appear in Appendix A.

It is necessary to state here that the water must be purified. This is done because an excessive concentration of iron or copper impurities can cause bulk glow in the vicinity of the test piece. Either distilled water or water purified by ion exchanger cartridges can be used. The ion exchangers (Barnstead Standard Type 0802) have been used because they are the most inexpensive and convenient way of obtaining the large amount of purified water required (1500 liters for a full tank).

In the early stages of the study, a small Howland² type apparatus was constructed for familiarization with the technique. In addition

the effect of replacing KCl with NaCl was investigated. The sodium chloride appeared to provide the same glow intensity as the potassium chloride. It was further determined that the amount of NaCl could be reduced to one third its original amount without any apparent loss of intensity. Finally it was determined that the same results could be obtained with technical grade NaCl substituted for the reagent grade. These factors will provide a financial savings for future investigators. In this study potassium chloride was used because of the large quantity on hand at the outset.

III. DISCUSSION OF RESULTS

A. General

In this study separation and transition were the flow phenomena of primary interest. It was expected that using circular cylinders and flat plates as models, visual evidence of separation and transition would be obtained. The glow pattern should appear as an even blue glow on the surface of the anode in laminar flow up to the point of separation. The glow should disappear along the separated region giving the appearance of a black line or region against the blue glow. Transition was expected to take the form of wavy regions in the glow or perhaps an increased light intensity beginning at the transition point.

B. Circular Cylinder

The circular cylinder was chosen as a model to be studied because of its simple geometry. The fact that some experimental data is available for the separation point on a cylinder in laminar flow also played a part in the decision to use a cylindrical model.

Test runs were conducted on two cylinders. One cylinder was 1.5 inches in diameter and 2 inches long; the other cylinder was 0.5 inch in diameter and 4 inches long. The tests were run to determine if a line of separation could be distinguished in the glow on the face of the cylinder. A line believed to be the line of separation was seen, and Figure 9 shows this line on the 0.5-inch and the 1.5-inch diameter cylinders. The line on the 1.5-inch diameter cylinder was seen to occur at approximately $\phi = 89^\circ$ where ϕ is the angle measured from the

III. DISCUSSION OF RESULTS

A. General

In this study, separation and condensation were the two phenomena of primary interest. It was expected that small cylindrical and flat plates as models, without evidence of separation and condensation would be obtained. The flow pattern should appear as in Figure 1. The flow in the center of the nozzle is taken up by the point of separation. The flow should disappear along the separated region. Giving the appearance of a flat line in section across the flow area. Transition was expected to take the form of wavy regions in the flow or perhaps an increased light intensity beginning at the transition point.

B. Cylindrical Cylinders

The circular cylinder was chosen as a model to be studied because of its simple geometry. The first part was experimental work is similar to the flow separation point in a cylinder. The flow also gives a picture of the transition to a turbulent state.

Two runs were conducted on two cylinders. One cylinder was 1.2 inches in diameter and 2 inches long. The other cylinder was 0.8 inch in diameter and 1 inch long. The water was run to determine if a flow of separation could be distinguished in the flow on the face of the cylinder. A flow believed to be the kind of separation was shown and Figure 2 shows this flow on the 0.8-inch and the 1.2-inch diameter cylinders. The flow on the 1.2-inch diameter cylinder was seen in Figure 3. The flow on the 0.8-inch cylinder was seen in Figure 4.

forward stagnation point (considering the flow to be ideal with no circulation) to a point on the surface of the cylinder in a plane perpendicular to the axis of the cylinder. The observed line remained very nearly stationary at various Reynolds numbers. This agrees with the solution of Thwaites,¹² equations for the separation point in laminar flow using the velocity distribution around a cylinder in irrotational flow given by potential theory. Figures 10 and 11 show this line at various Reynolds numbers for the 0.5- and 1.5-inch diameter cylinders, respectively. While no attempt was made to measure exact angles on the 0.5-inch diameter cylinder, it was seen that the line occurred at approximately the same angle ϕ in all runs on both cylinders. This is in agreement with results using Thwaites,¹² method with potential theory velocity distribution around a cylinder in irrotational flow. Comparison of Figures 10 and 11 confirms this statement. It will be noticed that the line on the 1.5-inch cylinder curves downward at the ends of the cylinder (see Figure 11) while this is not so in the case of the 0.5-inch cylinder (see Figure 10). This is attributed to cylinder end effects since in both cases the cylinder glowing length is 2 inches, but the total length of the 1.5-inch diameter cylinder is only 2 inches while that of the 0.5-inch diameter cylinder is 4 inches. All indications are that the observed line is the line of separation.

Schlichting⁵ cites the work of Hiemenz who in his thesis to Goettingen University in 1911 reported measurements of the pressure distribution around a cylinder in steady flow. Using the measured pressure distribution as a basis, he calculated that ϕ at separation

should be 82 degrees. He observed ϕ at separation on a cylinder to be 81 degrees. Schlichting also mentions the work of Flachsbert who experimented with cylinders in 1932. He determined that if the Reynolds number (based on cylinder diameter) were below a certain critical value (3×10^5), then the pressure minimum on the cylinder occurs at approximately $\phi = 70^\circ$, and separation would almost certainly occur before $\phi = 90^\circ$. If the Reynolds number were above the critical value, then the pressure minimum would occur near $\phi = 90^\circ$, and separation would occur approximately as indicated by potential theory. In the present study the highest Reynolds number obtained over a cylinder was 1.3×10^5 which is below the critical value, and hence it can be expected that separation will occur before $\phi = 90^\circ$.

Using Thwaites,¹² method (see Appendix B) with the ideal flow velocity distribution around a cylinder, the value of ϕ at separation was calculated. The value obtained ($\phi = 102^\circ$) is somewhat greater than the observed $\phi = 89^\circ$. This can be attributed to using the potential steady flow velocity distribution around the cylinder instead of a measured velocity or pressure distribution.

As a final confirmation, photographs were taken of smoke flow over a 1.5-inch diameter cylinder in a wind tunnel. The Reynolds number was 735. Figure 15c shows the result of smoke flow over the cylinder and confirms that separation occurs with ϕ between 85 and 90 degrees. It is concluded that the line observed on the cylinders used in this study is in fact the laminar flow line of separation.

about 10-15 degrees. The curves δ are plotted on a graph in
the 10 degrees. The following table shows the work of the
experiment with cylinders in 1957. The experiment was in the
number (based on cylinder diameter) was below a certain critical value
(1 to 10), then the pressure within the cylinder occurs as shown -
with $\delta = 10^\circ$, and sometimes with δ slightly greater than 10.
 $\delta = 20^\circ$. It was observed that above the critical value, the
the pressure within would occur with $\delta = 30^\circ$, and separation would
occur approximately at the end of the cylinder. In the present
work, the cylinder diameter was about 1.5 to 2.0
which is below the critical value, and hence it can be expected that
separation will occur below $\delta = 30^\circ$.

Using equation (1) (see Appendix B) with the local flow
velocity distribution around a cylinder, the value of δ in equation
was calculated. The value obtained ($\delta = 10^\circ$) is somewhat greater than
the observed $\delta = 10^\circ$. This can be attributed to using the potential
velocity distribution around the cylinder instead of a
realistic velocity or pressure distribution.

As a final comparison, photographs were taken of water flow
over a 1.5-inch diameter cylinder in a wind tunnel. The Reynolds num-
ber was 100. Figure 1 shows the results of water flow over the cylinder
and indicates that separation occurs with δ between 10 and 20 degrees.
It is concluded that the line observed on the cylinder must be due
to the flow in the wake of the cylinder.

C. Flat Plate

The flat plate was chosen as a model for study primarily because it was expected that a separated region would be visible at or near the leading edge. It was also hoped that reattachment of the separated flow to the plate might be observed.

Test runs were conducted on a flat plate model 5 inches long and 2-1/4 inches wide. The Reynolds number (based on a plate length of 5 inches) was varied as was the angle of attack. The test runs were conducted to determine if a line or region of separation could be distinguished in the glow over the flat plate.

A region, believed to be the separated region, was observed from the leading edge to approximately 0.1 to 0.2 inch downstream from the leading edge. Figures 12, 13, and 14 show this region for various angles of attack and Reynolds numbers. These observations suggest that separation is taking place at the leading edge of the flat plate, as expected. Photographs were taken of smoke flow over a flat plate in a wind tunnel to attempt to confirm that separation does occur at the leading edge. Figure 15a and b shows this flow at angle of attack 10 degrees and 15 degrees, respectively, at a Reynolds number of 2.4×10^3 (based on a flat plate length of 5 inches). It is seen that separation does in fact occur at the leading edge of the flat plate.

Immediately following the dark separated region is a bright region across the width of the plate. This region is almost a line, and it is believed that reattachment of the flow to the plate occurs here. Bourque and Newman⁶ experimented with small jets of fluid flowing over

C. Plan Table

The plan table was drawn on a sheet of paper, 10 inches by 14 inches.

It was intended that a separate sheet would be attached to the plan.

The drawing was made on the plan table, and the drawing was made on the plan table.

It was intended that a separate sheet would be attached to the plan.

The drawing was made on the plan table, and the drawing was made on the plan table.

It was intended that a separate sheet would be attached to the plan.

The drawing was made on the plan table, and the drawing was made on the plan table.

It was intended that a separate sheet would be attached to the plan.

The drawing was made on the plan table, and the drawing was made on the plan table.

It was intended that a separate sheet would be attached to the plan.

The drawing was made on the plan table, and the drawing was made on the plan table.

It was intended that a separate sheet would be attached to the plan.

The drawing was made on the plan table, and the drawing was made on the plan table.

It was intended that a separate sheet would be attached to the plan.

The drawing was made on the plan table, and the drawing was made on the plan table.

It was intended that a separate sheet would be attached to the plan.

The drawing was made on the plan table, and the drawing was made on the plan table.

It was intended that a separate sheet would be attached to the plan.

The drawing was made on the plan table, and the drawing was made on the plan table.

It was intended that a separate sheet would be attached to the plan.

The drawing was made on the plan table, and the drawing was made on the plan table.

It was intended that a separate sheet would be attached to the plan.

The drawing was made on the plan table, and the drawing was made on the plan table.

It was intended that a separate sheet would be attached to the plan.

The drawing was made on the plan table, and the drawing was made on the plan table.

It was intended that a separate sheet would be attached to the plan.

inclined flat plates. They observed separation at the leading edge of the flat plates and reattachment downstream from the leading edge. The small jets (0.187 inch in diameter and smaller) flowing over inclined plates do not exactly correspond to the circumstances of the present study where a 4-inch diameter circular fluid channel is provided for flow over models. The general circumstances of incompressible, two-dimensional flow over flat plates is the same, however, and qualitative comparisons should be valid. Bourque and Newman⁶ experimented with angles of attack of 30 degrees and greater. They showed that separation occurs at the leading edge of the flat plates which is in agreement with the observations of the present study. They showed that reattachment occurs further downstream from the leading edge as the angle of attack is increased. The experimental results of Bourque and Newman when extrapolated to the angles of attack used in the present study (0.5 degree to 13.1 degrees) indicate that reattachment occurs very near the leading edge of the plate. This is in agreement with the observations of the present study. Figure 14 shows the flow over a flat plate at various angles of attack at Reynolds number (based on flat plate length of 5 inches) of 1.28×10^5 . It can be seen that at angles of attack of 0.5 degree, 2.5 degrees, and 3.2 degrees (Figures 14a, b, and c, respectively), reattachment occurs at approximately the same location near the leading edge of the flat plate, but as the angle of attack is increased to 13.1 degrees (Figure 14d) reattachment occurs further downstream from the leading edge. On the basis of this qualitative evidence, it is concluded that reattachment of the flow to a flat plate is observable using the technique of electrochemiluminescence.

included this figure. The observed variation of the field with
of the field and measured distance from the field edge
The results (not shown in figures and tables) showing that
indicated that the field was not really constant in the direction of the
position, except about a 4-inch diameter circle. Field strength is pro-
portional to the square of the distance. The general character of the
the field strength. The field strength is the same, however, and
qualitative comparison should be made. Figures and tables
showed that angles of about 30 degrees and smaller. The field
that variation occurs in the field edge of the field and is
in agreement with the character of the present work. The
showed that relationship between the field strength and the field
edge at the edge of the field is the same. The experimental results
of figures and tables show that the field is not really constant
in the present work (0.5 degree to 13.5 degree) angles and distance.
and other work, the field edge of the field. This is in agree-
ment with the character of the present work. Figure 10 shows the
that the field strength is not really constant at angles of 30 degrees
(about the field edge of 3 degrees) at 1.5×10^2 . It can be seen
that the angles of about 0.5 degree, 0.5 degree, and 3.5 degrees
(Figure 10) are in agreement. The relationship between the field
strength and the field edge of the field is the same, however, and
in the field of about 13.5 degree to 13.5 degree (Figure 10) angles.
and other work, the field edge of the field. The results of
this qualitative estimate, it is concluded that the field strength is the
to a field in comparison with the field edge of the field.

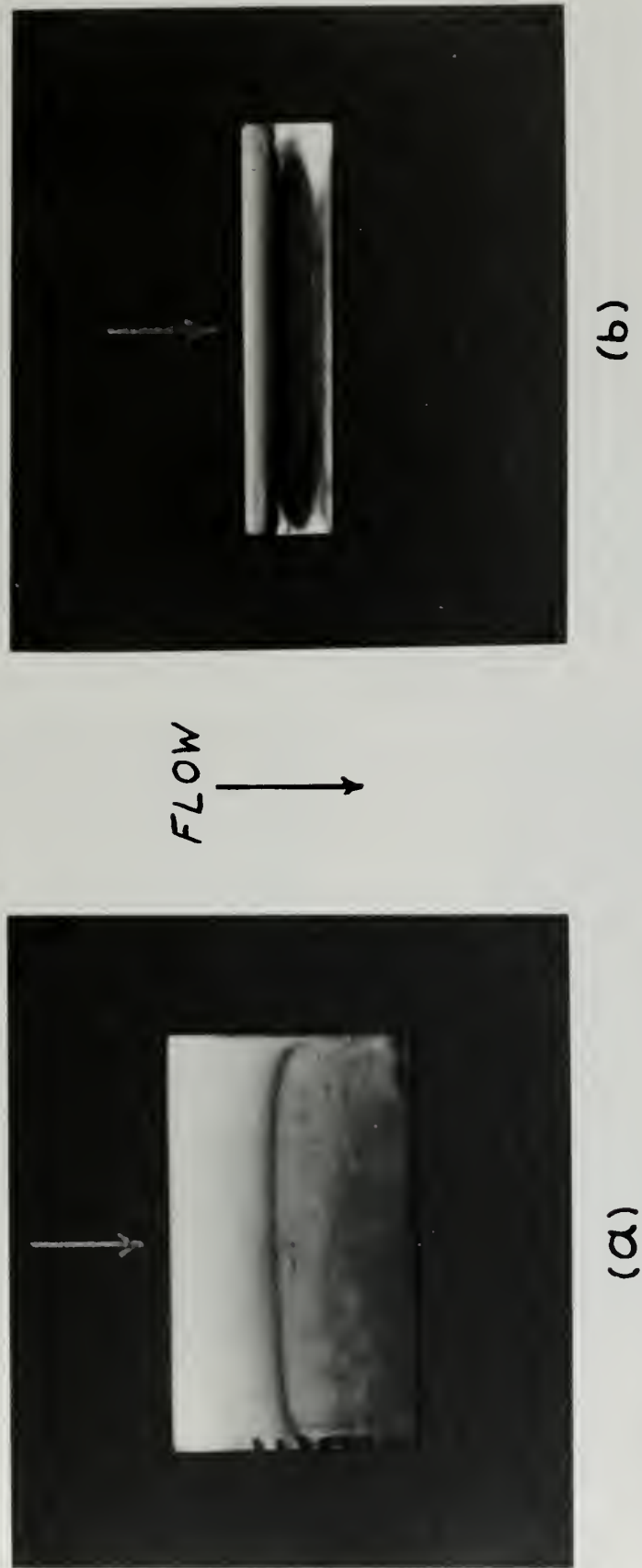


FIGURE 9. Line of separation on cylinders. Diameter (a) $d = 1.5$ inches, (b) $d = 0.5$ inches. Reynolds number (based on diameter) (a) $Re = 17,100$, (b) $Re = 5,700$.

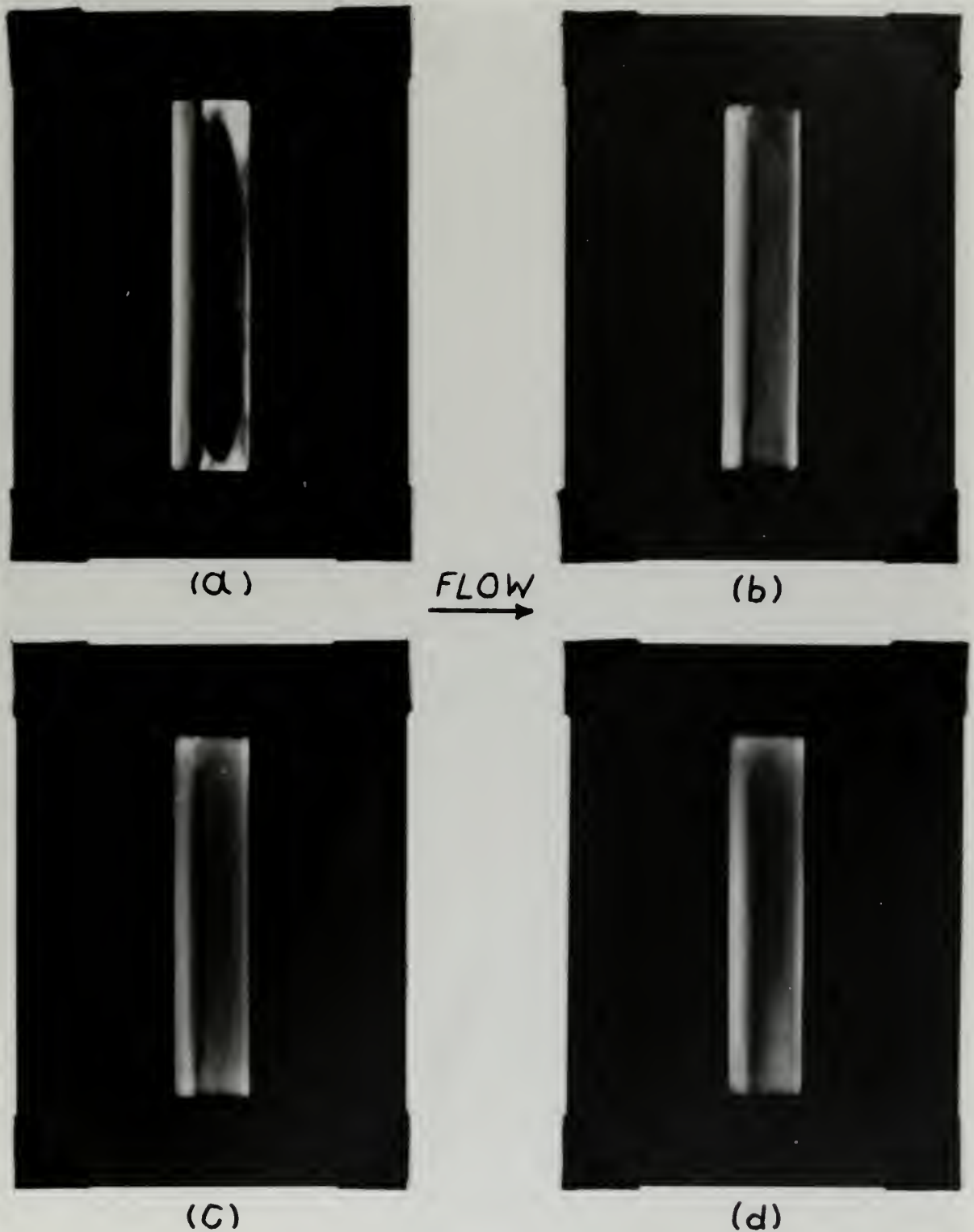


FIGURE 10. Line of separation on cylinders at various Reynolds numbers (based on cylinder diameter of 0.5 inches) (a) $Re = 5,700$ (b) $Re = 15,100$ (c) $Re = 35,300$ (d) $Re = 43,300$.

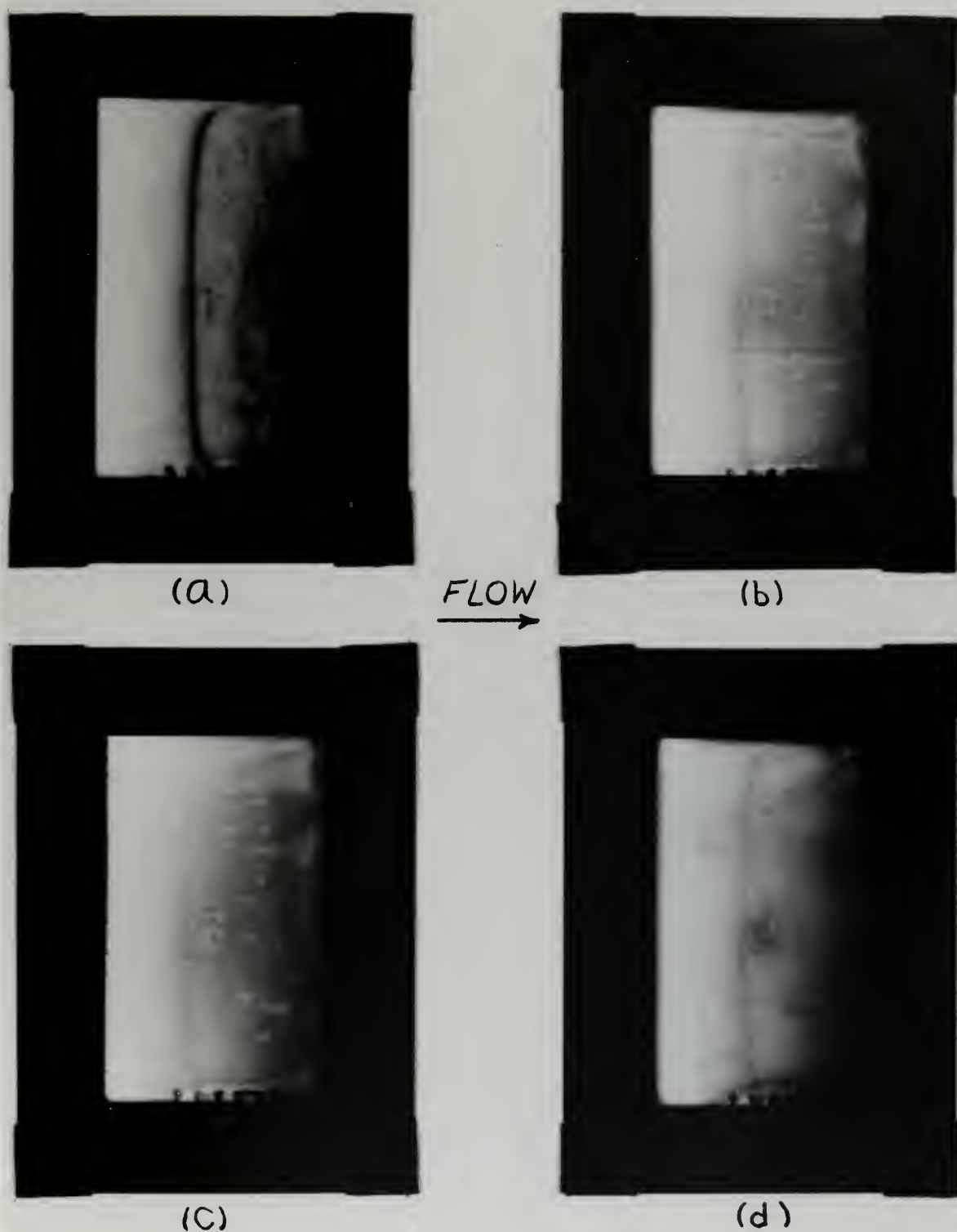


FIGURE 11. Line of separation on cylinders at various Reynolds numbers (based on cylinder diameter of 1.5 inches) (a) $Re = 17,100$ (b) $Re = 45,300$ (c) $Re = 106,000$ (d) $Re = 130,000$.

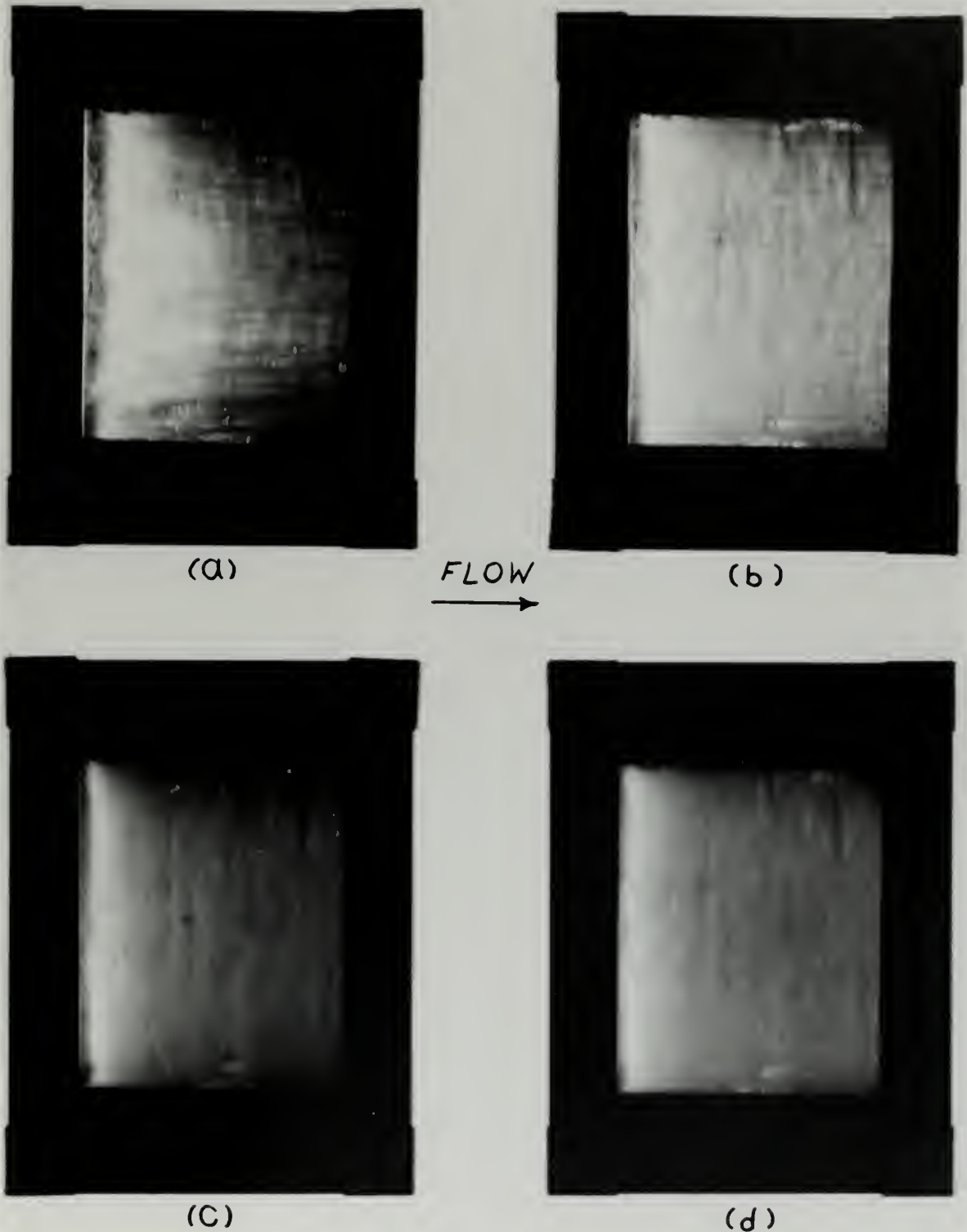


FIGURE 12. Separation on a flat plate at various Reynolds numbers. Angle of attack = 0.5° . Reynolds number (based on plate length of 5 inches) (a) $Re = 128,000$ (b) $Re = 253,000$ (c) $Re = 350,000$ (d) $Re = 430,000$.

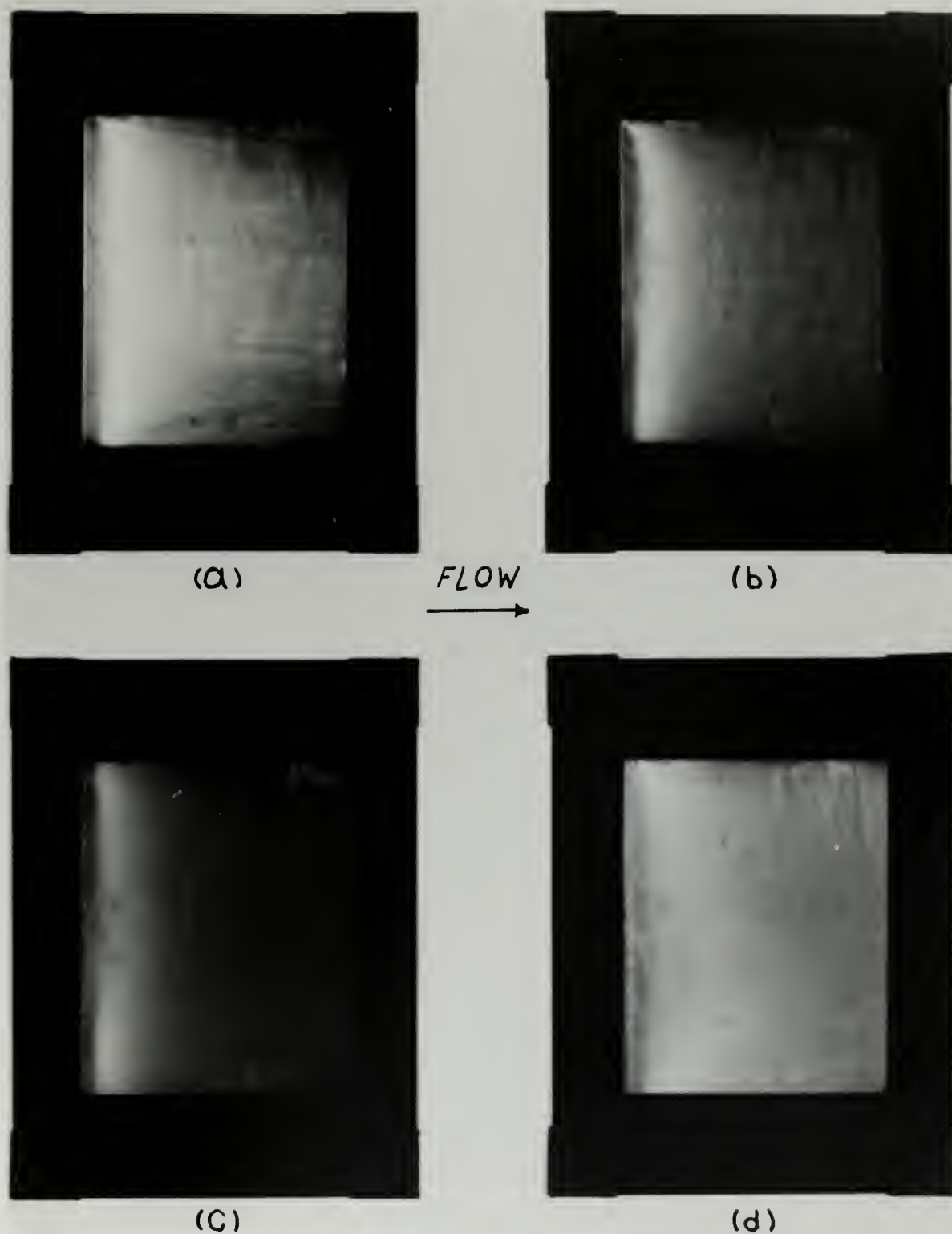


FIGURE 13. Separation on a flat plate at various Reynolds numbers. Angle of attack $= 2.5^\circ$. Reynolds number (based on plate length of 5 inches) (a) $Re = 128,000$ (b) $Re = 253,000$ (c) $Re = 350,000$ (d) $Re = 430,000$.

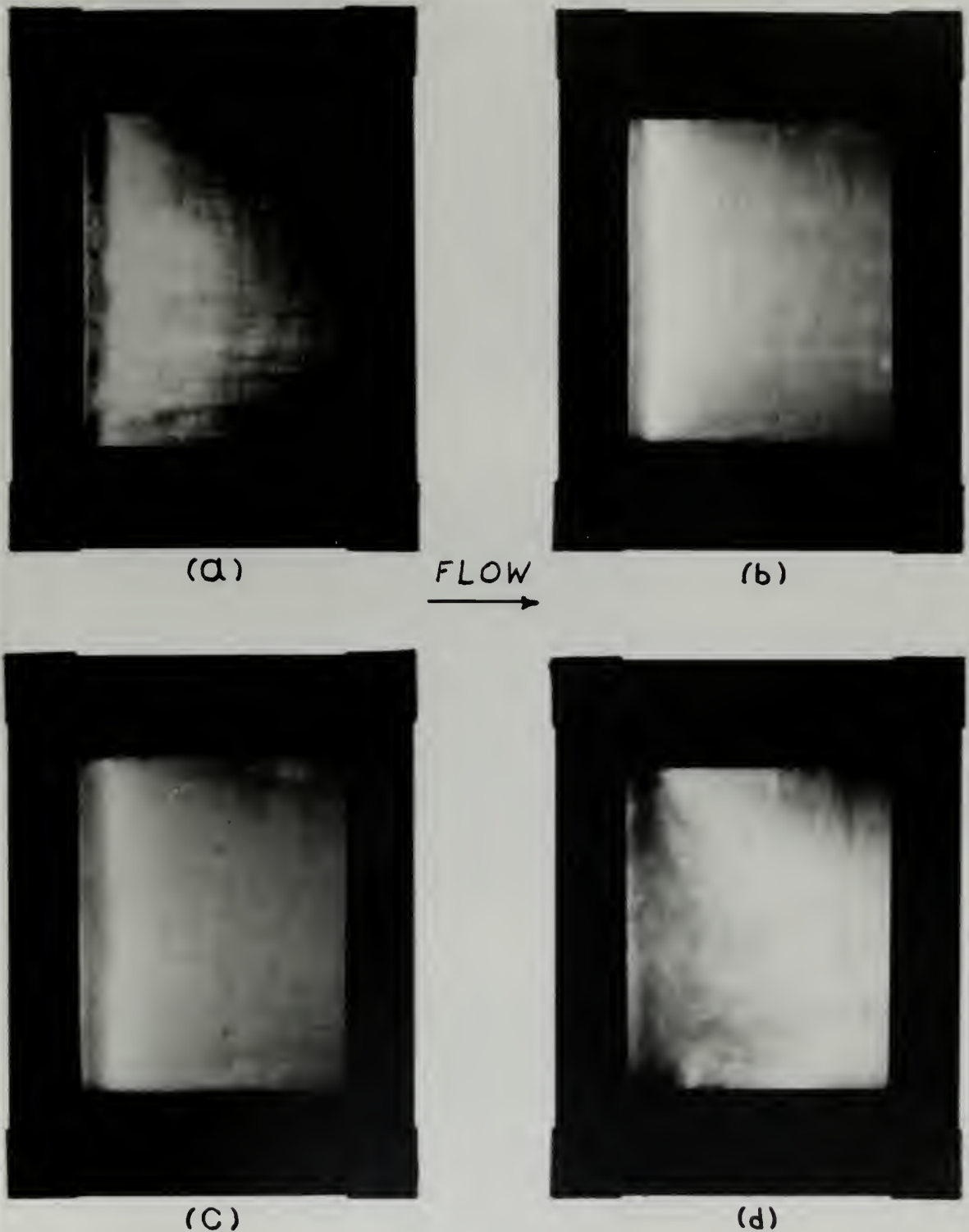


FIGURE 14. Separation on flat plate at various angles of attack. Angle of attack (a) $\alpha = 0.5^\circ$ (b) $\alpha = 2.5^\circ$ (c) $\alpha = 3.2^\circ$ (d) $\alpha = 13.1^\circ$. Reynolds number (based on flat plate length of 5 inches) $Re = 128,000$.

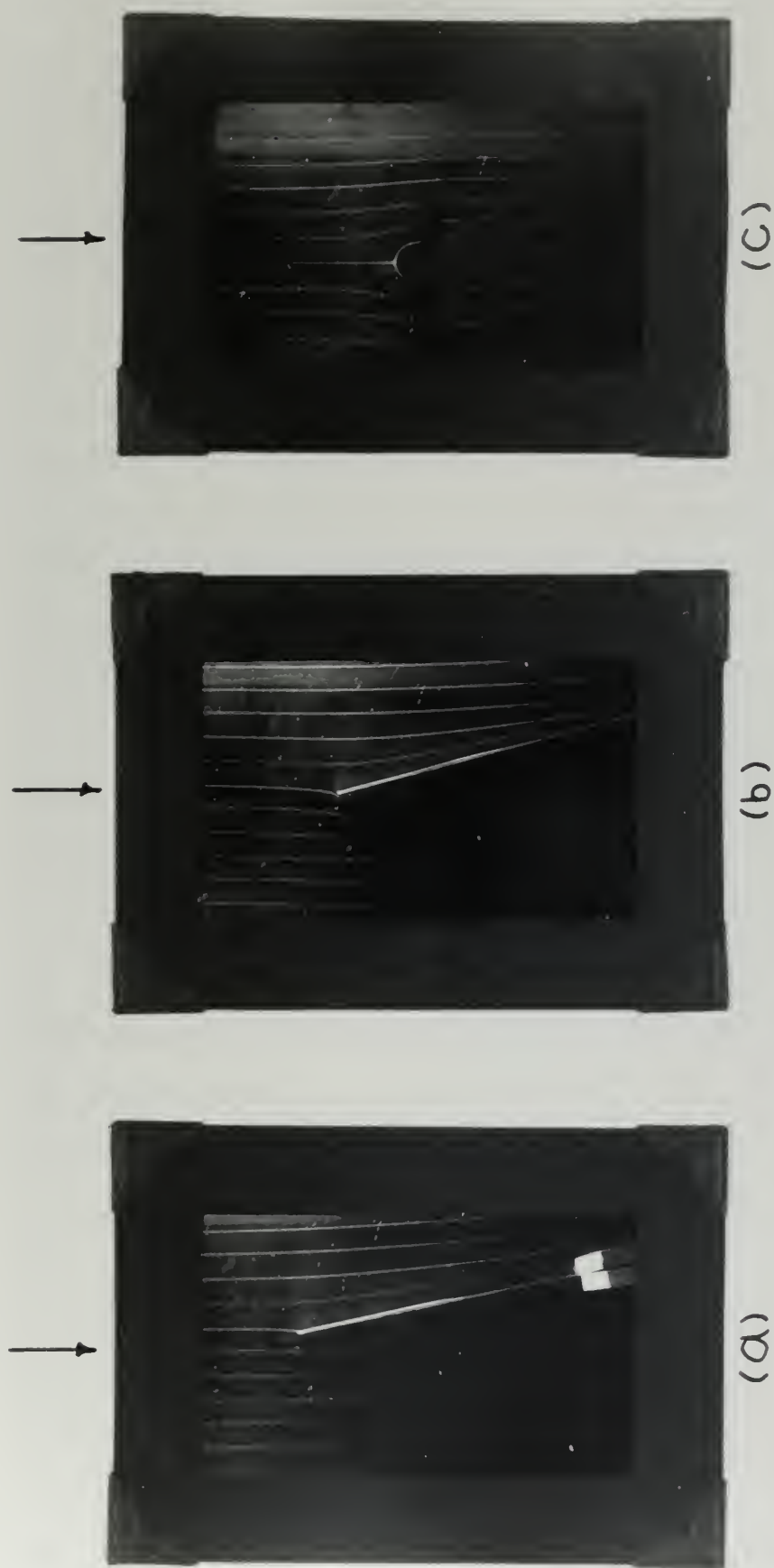


FIGURE 15. Separation on flat plate and cylinder in wind tunnel. Flat plate angle of attack (a) $\alpha = 10^\circ$ (b) $\alpha = 15^\circ$ Reynolds number (based on flat plate length of 5 inches and cylinder diameter of 1.5 inches) (a) $Re = 2,400$ (b) $Re = 2,400$ (c) $Re = 735$.

D. Transition

In this investigation an attempt was also made to visually observe transition from laminar to turbulent flow by applying the technique of electrochemiluminescence. Using this technique both Howland, et al.,² and Schiller³ observed glow patterns that could be interpreted as transition. Howland, et al.,² conducted tests of flow over a hydrofoil at various angles of attack. Some of their observed flow patterns resembled the transition spots obtained by Emmons,⁸ and some of their patterns were identified as transition streamers. Schiller³ studied flow patterns about turbulence stimulators similar to those used on ship hull models. He assumed turbulence existed and that his picture was typical of what the technique would show. The present objective was to determine whether or not the process of electrochemiluminescence could provide information directly related to transition.

It was decided to investigate classical transition on a flat plate at zero angle of incidence. Hansen¹⁰ experimentally determined the critical Reynolds number at which transition could first occur. His critical Reynolds number (based on distance to the onset of transition) is 3.2×10^5 . According to Schlichting⁷ this number should be considered the minimum required for transition. The experiments of Schubauer and Skramstad¹¹ indicate that at low turbulence, which probably exists in this apparatus, the onset of transition occurs at a $Re = 2.8 \times 10^6$ (based on distance from leading edge to onset of transition) and that fully turbulent flow should exist at $Re = 3.8 \times 10^6$.

In view of Hansen's¹⁰ critical Reynolds number, it was presumed that transition could be obtained on a long flat plate. Therefore, a

D. Transition

In this investigation an attempt was also made to identify the transition from laminar to turbulent flow by studying the variation of electrochemiluminescence. Using this technique both Howland, et al.,² and Schiller³ observed flow patterns that could be interpreted as transition. Howland, et al.,² conducted tests of flow over a cylindrical air vortex and angles of attack. Some of their observed flow patterns resembled the transition spots obtained by Hansen,¹⁰ and some of their patterns were identified as transition structures. Schiller³ studied flow patterns about turbulent airfoils similar to those used on ship hull models. He assumed turbulence existed and that the picture was typical of what the technique would show. The present objective was to determine whether or not the process of electrochemiluminescence could provide information directly related to transition.

It was decided to investigate classical transition on a flat plate at zero angle of incidence. Hansen¹⁰ experimentally determined the critical Reynolds number at which transition could first occur. His critical Reynolds number (based on distance to the onset of transition) is 3.2×10^5 . According to Schiller³ this number should be considered the minimum required for transition. The experiments of Schiller and Hansen¹¹ indicate that at low Reynolds numbers, which probably exist in this experiment, the onset of transition occurs at $Re = 2.6 \times 10^5$ (based on distance from leading edge to onset of transition) and that fully turbulent flow should exist at $Re = 3.6 \times 10^5$.

In view of Hansen's¹⁰ critical Reynolds number, it was presumed that transition could be obtained on a long flat plate. Therefore, a

1/4-inch plexiglass plate was constructed 2 inches wide and 30 inches long. The anode was made up of six platinum foil sections each 1 inch wide and 5 inches long. These sections were glued end to end with 1/4-inch overlap. This construction provided an anode 28.5 inches long. The cathode of 1/16-inch aluminum plate was 2 inches wide and 30 inches long. It was glued to the back of the plexiglass plate. The test piece was placed in the 4-inch test section at zero angle of incidence. Since the maximum available velocity in this test piece is 10.8 feet per second, the maximum obtainable Reynolds number is 2.47×10^6 (based on 28.5-inch length).

Observations were made throughout the range of available Reynolds numbers of 4×10^3 to 2.47×10^6 . Nothing unusual was seen that could be directly related to transition. However, three phenomena were noted. First, the glow intensity did increase as the flow velocity increased. Second, around a few rough spots the intensity was greater than elsewhere on the plate. The contrast of glow diminished as the velocity increased. These rough spots existed near where the foil sections overlapped. The spots resulted from difficulties experienced with gluing the platinum foil smoothly to the plate. Turbulent flow probably existed near these rough areas. If this is true then the above observation agrees with Schiller's³ observation of flow about turbulence stimulators. Therefore, it can be concluded that for some range of Reynolds numbers (with the upper limit undetermined), a short region of turbulent flow is indicated by increased glow intensity. The third phenomenon concerns streamers or lines which appeared on the long flat plate. Similar lines were observed on Schiller's³ flat plate and on the

[illegible]

short plate used in the separation studies. At low Reynolds numbers the lines appeared to originate at the leading edge. For higher Reynolds numbers beginning at about $Re = 1 \times 10^6$, they appeared to originate in the reattachment region. These lines were continuous and demonstrated a slight horizontal wavy motion. It is probable that the streamers observed by Howland, et al.,² were similar to these lines. Since these lines appeared even at subcritical Reynolds numbers, it is unlikely that Howland, et al., observed transition streamers.

One possible reason why transition was not observed in the first test is that the Reynolds number was too low. It was decided to exceed the Schubauer and Skramstad¹¹ critical Reynolds number of 2.8×10^6 by increasing the flow velocity. This was accomplished by reducing the test section diameter to 2 inches. Even though the contraction nozzle was not designed for this small section, a maximum velocity of 27.5 feet per second is obtained. This corresponds to $Re = 6.3 \times 10^6$ (based on length of platinum), which even exceeds the Schubauer and Skramstad¹¹ Reynolds number for fully turbulent flow of 3.8×10^6 .

For the second test the width of the flat plate was reduced by 1/8 of an inch to fit inside the 2-inch test section. The dimensions of the platinum section remained the same. The test piece was placed in the test section at zero angle of attack. Observations were made at Reynolds numbers from about 2×10^5 to 6.3×10^6 . As in the first test no phenomenon was observed that could be related to transition.

Since the tests described above did not provide information concerning transition, one final test was considered. Howland, et al.,² had demonstrated the feasibility of making wake studies with the

electrochemiluminescent technique. The wake studies of Hama, Long, and Hegarty⁹ have provided excellent information pertaining to the phenomenon of transition. Therefore, the present objective was to determine the feasibility of making a transition wake study using the technique of electrochemiluminescence.

Hama, Long, and Hegarty⁹ investigated flow over a trip wire on a flat plate at zero angle of incidence. The wire outside diameter was 1/16 inch, and the shortest plate used was 23 inches long. Flow patterns were obtained by injecting chrome blue or methylene blue dye in a narrow slit upstream of the trip wire. The test model was towed in a tank 2 feet wide, 2 feet deep, and 12 feet long. The towing velocities did not exceed 1 foot per second, and the Reynolds numbers varied from 260 to 560. With this technique Hama, et al., were able to observe the development of vortices behind a trip wire for a length of about 10 cm.

In order to investigate flow over a trip wire in the Schiller³ apparatus, a test piece was constructed consisting of a stainless steel rod as the anode and an aluminum plate as the cathode. Stainless steel was considered for the anode material because it was more available and cheaper than platinum and because it had been observed to glow in previous tests. The rod outside diameter is 1/16 inch. It is insulated from the plate by electrical tape, and it is located 6 inches from the leading edge. The 1/16-inch thick aluminum plate is 2 inches wide and 12 inches long. The test piece was placed in the original 4-inch test section. This was done because this test section provides better control of low velocity flow than the 2-inch

[illegible]

section. The resulting available Reynolds numbers varied from 400 to 5000. The plate was aligned at zero angle of attack.

The results of this test provided little of interest concerning transition. The flow velocity and applied voltage were both varied, but the wake length was never longer than $1/8$ of an inch. This short wake was only observed at the low Reynolds number of about 450. This test did prove one thing of significance. The glow on stainless steel was as intense as the glow on platinum foil. Even the line of separation was observed at high Reynolds numbers. The use of stainless steel as the anode material is promising and deserves more investigation.

In these tests the naked eye was the sole detector of light intensity. It was observed that glow intensity increased as the flow velocity increased up to about $Re = 4 \times 10^6$. Above this Reynolds number the glow appeared uniform along the plate and did not appear to the naked eye to change with increased flow velocity. Since Springer⁴ has shown that the electrochemiluminescent glow intensity is a direct function of mass transfer and since transition is accompanied by an increase in mass transfer toward the boundary, it may still be possible to detect the region of transition with an instrument such as a photo-multiplier tube.

IV. CONCLUSIONS

The evidence presented in this study has shown that lines of separation can be readily observed in laminar flow using the technique of electrochemiluminescence. A study of the applicability of this technique to separation in turbulent flow would be desirable.

Reattachment of fluid flow was observed on the flat plate. The technique of electrochemiluminescence promises to be a useful tool in the study of this phenomenon.

It is concluded from the tests conducted that transition can not be observed by the naked eye using the electrochemiluminescent technique. However, turbulent flow may be indicated by an increase in glow intensity. This phenomenon could be investigated by light intensity measurements with an instrument such as a photomultiplier tube.

INTRODUCTION

The evidence presented in this study has shown that there is a
close relationship between the amount of light entering the eye
and the amount of light leaving the eye. A study of the eye's
response to light is necessary for a better understanding of the
eye's function.

The amount of light entering the eye is determined by the
amount of light entering the eye. The amount of light entering
the eye is determined by the amount of light entering the eye.

It is concluded from the tests conducted that the amount of
light entering the eye is determined by the amount of light
entering the eye. The amount of light entering the eye is
determined by the amount of light entering the eye. The amount
of light entering the eye is determined by the amount of light
entering the eye. The amount of light entering the eye is
determined by the amount of light entering the eye.

V. REFERENCES

1. -----; "Symposium on Flow Visualization," Report of the ASME annual meeting, Nov. 1960.
2. Howland, B., Pitts, W. H., and Gesteland, R. C., "Use of Electrochemiluminescence for Visualizing Fields of Flow." Technical report 404, Massachusetts Institute of Technology, Research Laboratory of Electronics, Sept. 1962.
3. Schiller, T. R., "An Apparatus for Applying the Technique of Electrochemiluminescence to Boundary Layer Studies." S. M. Thesis, Massachusetts Institute of Technology, Depts. of Mechanical Engineering and Naval Architecture and Marine Engineering, May 1964.
4. Springer, G. S., "The Use of Electrochemiluminescence in the Measurement of Mass Transfer Rates," The Review of Scientific Instruments, Volume 35, No. 10, October, 1964, pp. 1277-1280.
5. Schlichting, H., Boundary Layer Theory, 4th Edition, McGraw-Hill, 1962, p. 155.
6. Bourque, C. and Newman, B. G., "Reattachment of a Two-Dimensional Incompressible Jet to an Adjacent Flat Plate," Aero Quarterly, Vol. 11, 1959, p. 201.
7. Schlichting, H., Boundary Layer Theory, 4th Edition, McGraw-Hill, 1962, p. 37.
8. Emmons, H. W., "The Laminar Turbulent Transition in a Boundary Layer," Journal of Aeronautical Science, Volume 18, 1951, 490.
9. Hama, F. R., Long, J. D., and Hegarty, J. C., "On Transition from Laminar to Turbulent Flow," Journal of Applied Physics, Volume 28, 1957, 388.

7. REFERENCES

1. "Report on the Electricities," Report of the
the Royal Society, 1900.
2. H. A. Lorentz, "On the Theory of the
Electricity and Magnetism," *Archiv für
Electrodynamik und Magnetismus*, 1900, 1, 1.
3. "Theorie der Elektrizität," *Handbuch der
Physik*, 1900, 1, 1.
4. "Theorie der Elektrizität," *Handbuch der
Physik*, 1900, 1, 1.
5. "Theorie der Elektrizität," *Handbuch der
Physik*, 1900, 1, 1.
6. "Theorie der Elektrizität," *Handbuch der
Physik*, 1900, 1, 1.
7. "Theorie der Elektrizität," *Handbuch der
Physik*, 1900, 1, 1.
8. "Theorie der Elektrizität," *Handbuch der
Physik*, 1900, 1, 1.
9. "Theorie der Elektrizität," *Handbuch der
Physik*, 1900, 1, 1.

10. Hansen, M., "Velocity Distribution in the Boundary Layer of a Submerged Plate," NACA TM 585.
11. Schubauer, G. B. and Skramstad, H. K., "Laminar Boundary Layer Oscillations and Transition on a Flat Plate," NACA TR 909.
12. Thwaites, B., "Approximate Calculation of the Laminar Boundary Layer," Aero Quarterly, Volume 1, Nov. 1949, pp. 245-280.
13. Stratford, B. S., "Flow in the Laminar Boundary Layer Near Separation," R&M 3002, 1957.
14. Curle, N. and Skan, S. W., "Approximate Methods for Predicting Separation Properties of Laminar Boundary Layers," Aero Quarterly, Volume 8, Aug. 1957, pp. 257-268.
15. Sanborn, V. A., "Preliminary Experimental Investigation of Low Speed Turbulent Boundary Layer in Adverse Pressure Gradients," NACA TN 3031, 1953.
16. Tetervin, N. and Von Doenhoff, A. E., "Determination of General Relations for the Behavior of Turbulent Boundary Layers," NACA TR 772, 1943.
17. Townsend, A. A., "The Behavior of Turbulent Boundary Layer Near Separation," Journal of Fluid Mechanics, Volume 12, 1962, pp. 536-554.
18. Stratford, B. S., "The Prediction of Separation of the Turbulent Boundary Layer," Journal of Fluid Mechanics, Volume 5, pt. 1, Jan. 1959, pp. 1-16.
19. Maskell, E. C., "Approximate Calculation of the Turbulent Boundary Layer in Two-Dimensional Incompressible Flow," British Royal Aircraft Establishment (R.A.E.) Report Aero 2443, Nov. 1951.

10. Berman, H., "Velocity distribution in the boundary layer of a turbulent flow," *Trans. ASME*, 1957.
11. Berman, H. and Berman, H. K., "Turbulent boundary layer velocity and pressure on a flat plate," *Trans. ASME*, 1957.
12. Berman, H., "Approximate calculation of the turbulent boundary layer," *Trans. ASME*, 1957, pp. 517-520.
13. Berman, H. K., "Flow in the turbulent boundary layer over a curved surface," *Trans. ASME*, 1957.
14. Berman, H. and Berman, H. K., "Approximate methods for predicting turbulent flow over curved surfaces," *Trans. ASME*, 1957, pp. 521-524.
15. Berman, H. K., "Turbulent flow over curved surfaces," *Trans. ASME*, 1957, pp. 525-528.
16. Berman, H. and Berman, H. K., "Turbulent flow over curved surfaces," *Trans. ASME*, 1957, pp. 529-532.
17. Berman, H. K., "Turbulent flow over curved surfaces," *Trans. ASME*, 1957, pp. 533-536.
18. Berman, H. K., "Turbulent flow over curved surfaces," *Trans. ASME*, 1957, pp. 537-540.
19. Berman, H. K., "Turbulent flow over curved surfaces," *Trans. ASME*, 1957, pp. 541-544.
20. Berman, H. K., "Turbulent flow over curved surfaces," *Trans. ASME*, 1957, pp. 545-548.

20. Spence, D. A., "Development of Turbulent Boundary Layers," Journal of Aero Science, Volume 23, No. 1, 1956.
21. Schubauer, G. B. and Klebanoff, P. S., "Investigation of Separation of the Turbulent Boundary Layer," NACA TR 1030, 1951.
22. Ludwig, H. and Tillmann, W., "Investigation of the Wall-Shearing Stress in Turbulent Boundary Layers," NACA TM 1285, May 1950.
23. Moses, H., "The Behavior of Turbulent Boundary Layers in Adverse Pressure Gradients," Ph.D. Thesis, Massachusetts Institute of Technology, Dept. of Mechanical Engineering, 1964.

- [illegible]

APPENDICES

The first of these is the fact that the
the second is the fact that the
the third is the fact that the
the fourth is the fact that the
the fifth is the fact that the
the sixth is the fact that the
the seventh is the fact that the
the eighth is the fact that the
the ninth is the fact that the
the tenth is the fact that the

APPENDIX

The first of these is the fact that the
the second is the fact that the
the third is the fact that the
the fourth is the fact that the
the fifth is the fact that the
the sixth is the fact that the
the seventh is the fact that the
the eighth is the fact that the
the ninth is the fact that the
the tenth is the fact that the

APPENDIX A

Details of Chemiluminescent Solution

<u>SUBSTANCE</u>	<u>AMOUNT</u>	<u>PURPOSE</u>
H ₂ O	- - - - -	Solvent
KCl	1.0 Normal	Supporting electrolyte
KOH	0.01 Normal	Adjust pH
H ₂ O ₂	8.5×10^{-4} Normal	Oxidizing agent
Luminol*	4.4×10^{-3} Normal	Chemiluminescent substance

The kinematic viscosity of the solution was assumed to be the same as water at 70 °F.

* Eastman Kodak Company, Luminol = (5-amino-2, 3-dihydro-1, 4-phthalazinedione)

APPENDIX A

Details of Quenchless Solenoid

SUBSTANCE	ADJUST	POLE
H ₂ O	Belgium
HCl	1.0 mmol	hydrochloric acid
H ₂ SO ₄	0.01 mmol	adjust by
H ₂ O ₂	8.2 x 10 ⁻⁴ mmol	oxidizing agent
Iodine	4.4 x 10 ⁻³ mmol	quenchless substance

The magnetic viscosity of the solution was measured to be 100 and 1000 at 10 and 20 °C.

Yoshida Kōzō (Yoshida Kōzō, Iodine = (2-ethyl-2,2-dimethyl-1,4-dioxane))

APPENDIX B

Literature Survey of Flow Separation

I. Background

The boundary layer equations have defied exact solution except for the most simple cases. Phenomena of interest, such as the point of separation in a given flow, cannot be computed exactly. There are approximate solutions to the boundary layer equations, and the use of these has led to methods of predicting the point of separation for fluid flow over a body with reasonable engineering accuracy.

For the case of two-dimensional laminar external flow over a body, approximate solutions for the separation point have been worked out by Thwaites¹² and Stratford.¹³ Thwaites' method consists of linearizing the Navier-Stokes equation and examining experimental data to determine appropriate equation constants. Thwaites empirically determined a value of his equation parameter m , for which separation would occur ($m = 0.082$). The parameter $m = -\frac{\theta^2}{U} \frac{dU}{dx}$, where θ is the momentum thickness, $U(x)$ is the velocity in the free stream outside of the boundary layer, x is a coordinate taken along the surface of the body, and ν is the kinematic viscosity of the fluid. In this method it is assumed that $U(x)$ is known.

Stratford¹³ divides the boundary layer into two parts: an inner layer where viscosity is important and an outer layer where viscosity is unimportant and the flow is almost ideal. Stratford's method requires the solution of a single equation for x_s , the point along the surface of the body where separation occurs. The assumption used is that $\frac{\partial^2 \psi}{\partial x^2} = 0$,

Boundary Value Problems

I. Introduction

The boundary value problems have been solved in the case of the most simple cases. Problems of interest, such as the problem of separation in a given flow, cannot be solved exactly. There are approximate solutions to the boundary value problem, and the use of these has led to methods of solving the problem of separation for fluid flow over a body with variable cross-section.

For the case of two-dimensional incompressible fluid flow over a body, approximate solutions for the separation point have been found by the method of ¹Prandtl and ²Glauert, which consists of linearizing

the Prandtl-Glauert equation and assuming separation data to determine appropriate equation coefficients. The linearized equation is valid of the separation point of the flow which separation occurs ($\alpha = 0.05^\circ$).

The parameter $\alpha = \frac{U}{V_\infty}$, where θ is the maximum deflection, $U(x)$ is the velocity in the flow stream outside of the boundary layer, V_∞ is a reference velocity along the surface of the body, and χ is the kinematic viscosity of the fluid. In this report it is assumed that $U(x)$ is known.

³Glauert divides the boundary layer into two parts: an inner layer where viscosity is important and an outer layer where viscosity is unimportant and the flow is almost ideal. Glauert's method requires

the solution of a single equation for χ . The point along the surface at

the body where separation occurs. The separation point is then $\frac{6}{\chi} = 0$.

where x is a coordinate along the surface of the body, and p is the static pressure. The join between the inner and outer layers is postulated to be continuous in u , $\partial u / \partial y$, $\partial^2 u / \partial y^2$, and ψ , the stream function. Here u is the velocity inside the boundary layer in the x direction, and y is a coordinate perpendicular to the surface of the body. The solution for the outer layer is obtained by superimposing solutions of Bernoulli's equation for ideal flow and the Blasius solution of the boundary layer with no pressure gradient. In the inner layer where the viscous forces are very large, a solution is obtained by equating the viscous and pressure forces. The solutions for the inner and outer layers and the postulated boundary conditions are enough to determine the velocity profile and the equation for separation except for a coefficient which is dependent upon $\partial^2 p / \partial x^2$. The value of the coefficient can be changed as appropriate by empirical methods for $\partial^2 p / \partial x^2$ other than zero. Stratford's method requires a knowledge of $U(x)$ and the pressure distribution along the body.

Curle and Skan¹⁴ have modified Thwaites' method by changing the value of the parameter determining separation to $m = 0.090$. The Curle and Skan modification to the Stratford method consists of changing the empirical coefficient in the Stratford equation. Curle and Skan indicate that the Stratford method is slightly the more accurate of the two, but it cannot be used to compute such boundary layer parameters as the momentum thickness (θ), which can be calculated using Thwaites' method.

Since it will be of interest to know θ at the point of transition to turbulence and since the accuracies of Thwaites' and Stratford's

methods are not very different, it was decided to use Thwaites' method as modified by Curle and Skan as the primary means of predicting the laminar flow separation point. Thwaites' method is described in more detail in the following section.

For the case of turbulent external flow over a body, numerous methods (e.g., Refs. 15-20) have been developed for predicting the separation point. Among these are the work of Von Doenhoff and Tetervin¹⁶ in determining general equations for boundary layer parameters such as θ and predicting the point of separation of fluid flow over a body. The criterion they used for predicting separation was that separation occurs when the shape parameter $H = 2.6$ where $H = \delta^*/\theta$ and δ^* is the displacement thickness. This criterion was confirmed experimentally by Schubauer and Klebanoff.²¹

Townsend¹⁷ and Stratford¹⁸ have developed methods of calculating the separation point in turbulent flow. Their methods are based on the pressure distribution along a body and its behavior at or near separation.

Maskell¹⁹ developed a method for calculating the turbulent boundary layer for which the separation criterion is the requirement that the skin friction (C_f) goes to zero at the point of separation. This method utilizes the Ludwig-Tillmann²² skin friction formulation considered by others (Refs. 15, 18, and 23) as probably the best available. Sanborn¹⁵ concurs in the accuracy and usefulness of Maskell's method.

It was decided to concentrate primarily on laminar flow in this study, but if time and the experimental apparatus permitted, turbulent flow would be treated also. For turbulent flow Maskell's method appears

although are not very different, it was decided to use the term 'series' as applied to the data and the primary series of recording the various flow measurements. (The term 'series' is applied in some cases, in the following sections.)

For the case of subject groups there were a half, numerous subjects (4-12, 13-20) have been developed for individual life

aggregates. These are the sets of the 'series' and 'series' in individual series for individual data series, and in

it was decided to use the term of 'series' of data for a half. The

subject groups for individual series for individual series occur

when the data series is 2^2 or 2^3 and 2^4 is the data-

series. This is the case for individual series for individual

and 'series'.

For the 'series' and 'series' series developed series of individual

the 'series' series is individual data. These series are based on the

series developed series a half and the series of a half series-

series.

Series¹⁰ developed a method for calculating the individual series

from the data. The series series is the series series the

also the series (2²) series to form at the point of series. The series

will use the 'series' series¹¹ this is the 'series' series

series (series, 2², 2³, 2⁴) as series the series series.

series in the series and series of series series.

It was decided to use the term 'series' for series in the

series, but it is the series series series series.

There would be series series. The series series series series

to be most accurate while Stratford's method is simpler to apply. Stratford's method should then be a good check on the results as given by Maskell.

II. Brief Description of the Method of Thwaites¹² for Predicting the Point of Separation in a Two-Dimensional Flow Over a Body

The Navier-Stokes equation with Prandtl's approximations for a two-dimensional boundary layer may be written as:

$$\frac{d\theta}{dx} = -(H + 2) \frac{dU}{dx} \frac{\theta}{U} + \frac{\nu}{U^2} \left(\frac{\partial u}{\partial y} \right)_{y=0} \quad (1)$$

The momentum thickness (θ) is given empirically (Ref. 12) by:

$$\theta^2 = 0.45 U^{-6} \nu \int_0^x U^5 dx \quad (2)$$

Define the parameters m , n , and L as follows:

$$m = - \frac{\theta^2}{\nu} \frac{dU}{dx} \quad (3)$$

$$n = \frac{\theta}{U} \left(\frac{\partial u}{\partial y} \right)_{y=0} \quad (4)$$

$$L = \frac{U}{\nu} \frac{d(\theta^2)}{dx} \quad (5)$$

Taking $\frac{d(\theta^2)}{dx} = 2 \theta \frac{d\theta}{dx}$ and rearranging (1) gives:

$$\frac{d(\theta^2)}{dx} = 2(H + 2) \frac{m\nu}{U} + \frac{2\nu}{U} n \quad (6)$$

Rearranging (6) gives:

$$L = 2 [m(H + 2) + n] \quad (7)$$

no be more accurate a line of thought? and is it not a good thing to have
Christians' minds fixed upon the fact that the world is not
of itself.

12. What is the value of the world of things? The world of things
is of value in a two-fold sense: first, as a source
of pleasure and comfort, and second, as a source of
knowledge and wisdom.

(1)
$$\frac{d}{dx} \left(\frac{1}{x} \right) = -\frac{1}{x^2} = -\frac{1}{x^2} \cdot \frac{1}{x} = -\frac{1}{x^3}$$

The function $f(x) = \frac{1}{x}$ is given above. (See Ex. 10.)

(2)
$$\int_0^1 x^2 dx = \left[\frac{x^3}{3} \right]_0^1 = \frac{1}{3}$$

Let us now consider the function $f(x) = x^2$.

(3)
$$\frac{d}{dx} \left(\frac{1}{x} \right) = -\frac{1}{x^2}$$

(4)
$$\frac{d}{dx} \left(\frac{1}{x^2} \right) = -\frac{2}{x^3}$$

(5)
$$\frac{d}{dx} \left(\frac{1}{x^3} \right) = -\frac{3}{x^4}$$

Let us now consider the function $f(x) = \frac{1}{x}$.

(6)
$$\frac{d}{dx} \left(\frac{1}{x} \right) = -\frac{1}{x^2}$$

Let us now consider the function $f(x) = x^2$.

(7)
$$\frac{d}{dx} (x^2) = 2x$$

Thwaites found equation (7) to be nearly linear in m and chose $L = 0.45 + 6m$. By inspecting experimental data he determined that separation should occur at $m = 0.082$. The Curle and Skan¹⁴ modification gives $m = 0.090$ at separation. Solving equation (7) for H at separation (using $m = 0.090$), $n = 0$ (since $[\partial u / \partial y]_{y=0}$) and $H = 3.5$ which is a more familiar criterion for separation than is the value of the parameter m .

Finally at separation:

$$0.090 = -\frac{\theta^2}{\nu} \frac{du}{dx} = -\frac{0.45}{U^6} \frac{du}{dx} \int_0^{x_{\text{sep}}} U^5 dx \quad (8)$$

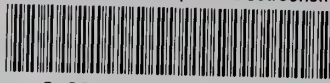
Solving equation (8) for x_{sep} gives the position of separation in the laminar flow.

Symbols

x, y	Coordinate axes parallel to the surface and perpendicular to it, respectively.
L, m, n	Parameters defined in Section II.
H	Shape parameter; given as δ^* / θ .
θ	Momentum thickness; given as $\int_0^\infty \frac{u}{U} (1 - \frac{u}{U}) dy$.
δ^*	Displacement thickness; given as $\int_0^\infty (1 - \frac{u}{U}) dy$.
u	Velocity inside the boundary layer in the x direction.
U	Free stream velocity outside the boundary layer.
ν	Kinematic viscosity of the fluid.

thesA232

A study of the technique of electrochemi



3 2768 001 90914 6

DUDLEY KNOX LIBRARY